HBT type measurements in quantum optics experiments

Sébastien Tanzilli

Team "Quantum Information with Light & Matter"

UMR 7336

Laboratoire Physique de la Matière Condensée

HBT Workshop, Observatoire de la Côte d'Azur, Nice, May12-13 2014

Outline

1. **Introduction**
   1. Standard HBT setup & classical description of $g^{(2)}(0)$
   2. HBT in quantum optics / experimental tools
   3. Quantum description of $g^{(2)}(0)$
   4. The context of quantum communication
2. **HBT for characterizing single photon sources (SPS)**
3. **HBT for characterizing photon pair sources**

1.1 The HBT setup: a bright idea for Astrophysics

- **HBT - original method**

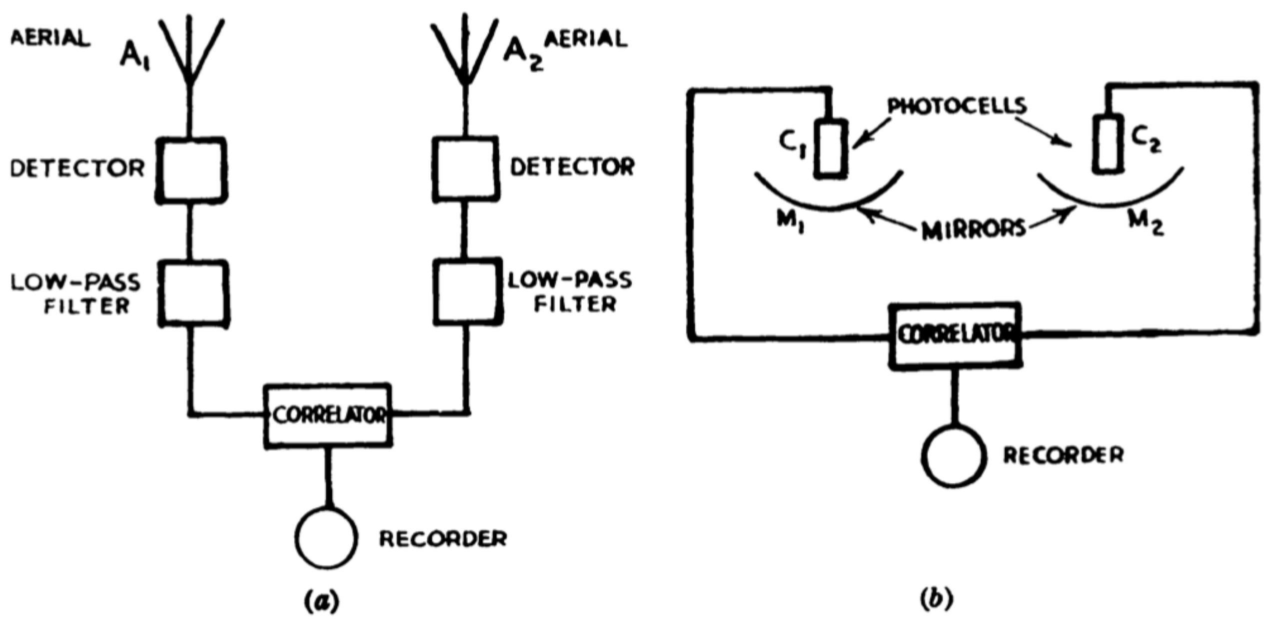

Fig. 1. A new type of radio interferometer (*a*), together with its analogue (*b*) at optical wave-lengths

R. Hanbury Brown and R. Q. Twiss, Nature **177**, 27-32 (1956)

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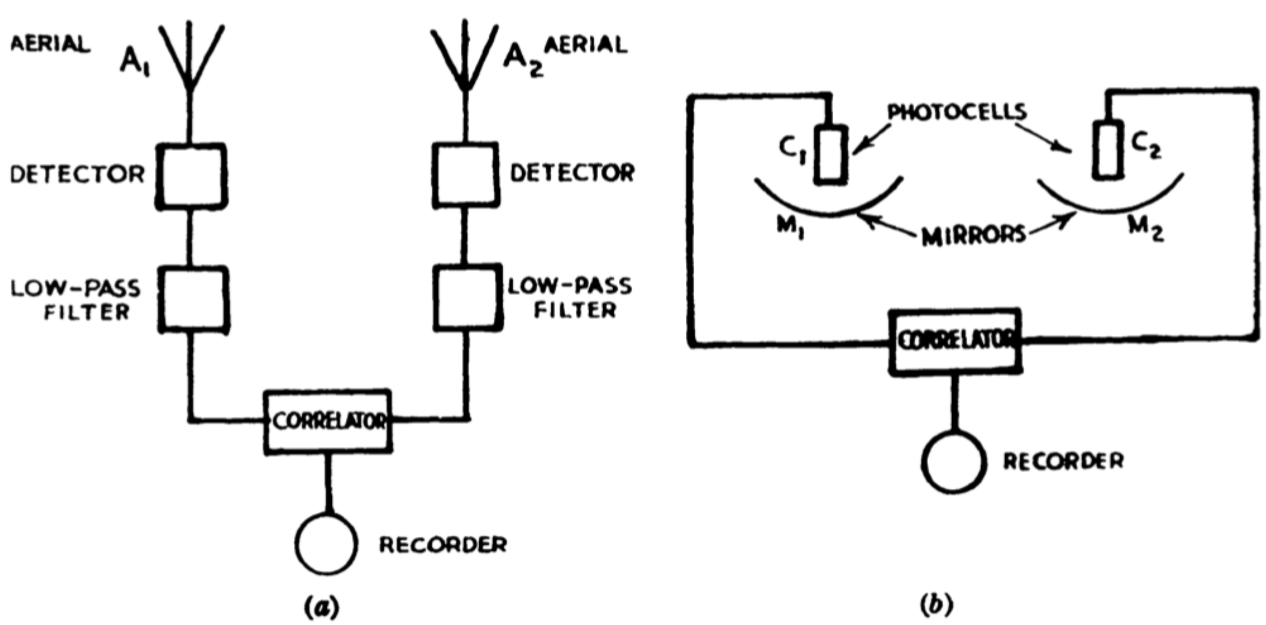

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What for ?

Measurement of the spatial coherence area ➜ angular diameter of a star

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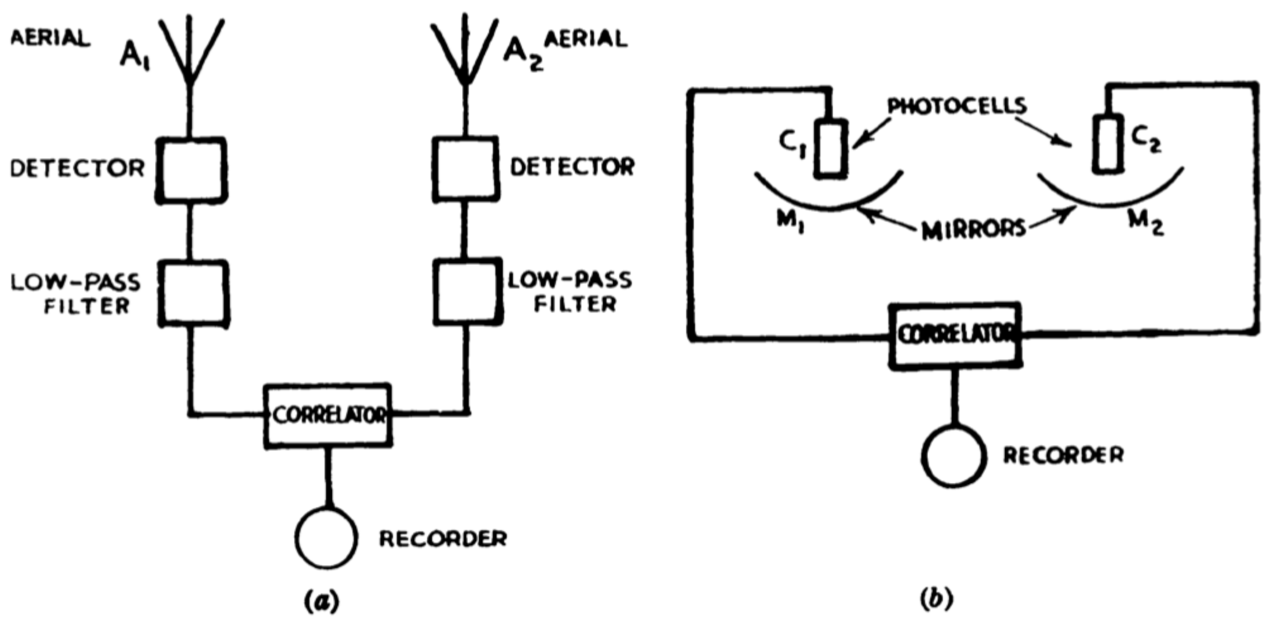

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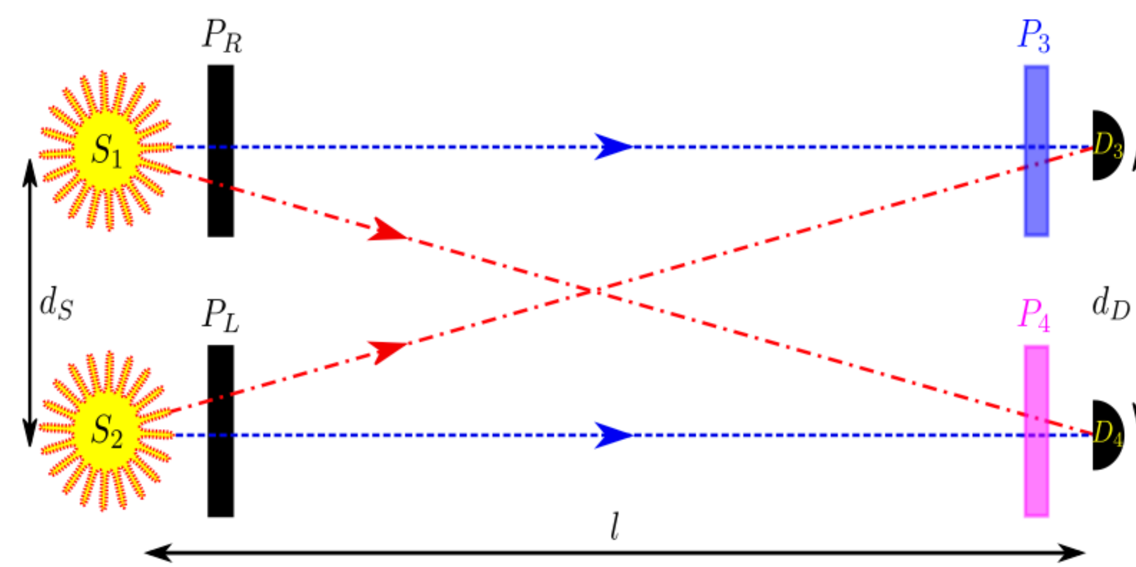

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Interferometer-like configuration insensitive to atmospheric fluctuations !

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1.1 Classical description of the autocorrelation function

- **Classical intensity correlation in the time domain**

$$g^{(2)}(t_1, t_2) = \frac{\langle E^\star(t_1)E^\star(t_2)E(t_2)E(t_1)\rangle}{\sqrt{\langle|E(t_1)|^2\rangle\,\langle|E(t_2)|^2\rangle}} = \frac{\langle I(t_1)I(t_2)\rangle}{\langle I(t_1)\rangle\,\langle I(t_2)\rangle}$$

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Remarking $\langle I^2(t)\rangle \geq \langle I(t)\rangle^2$

$\mapsto g^{(2)}(0) \geq 1$

Classical $g^{(2)}(0)$ is always greater than 1 !

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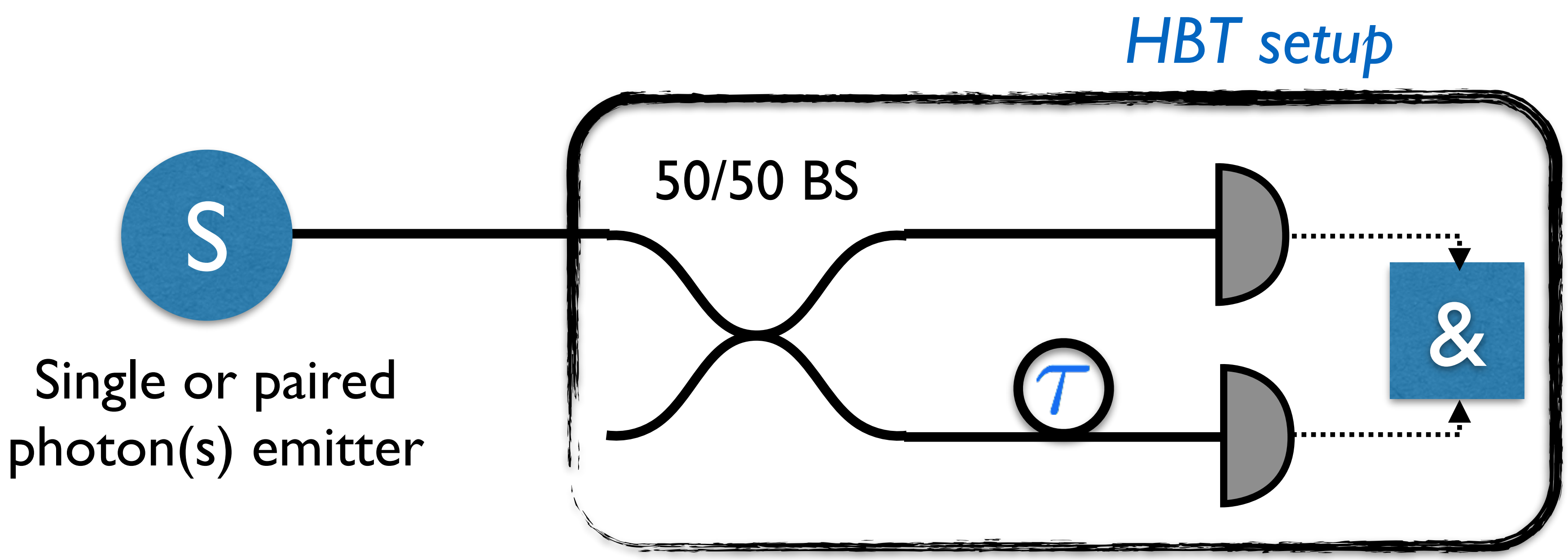

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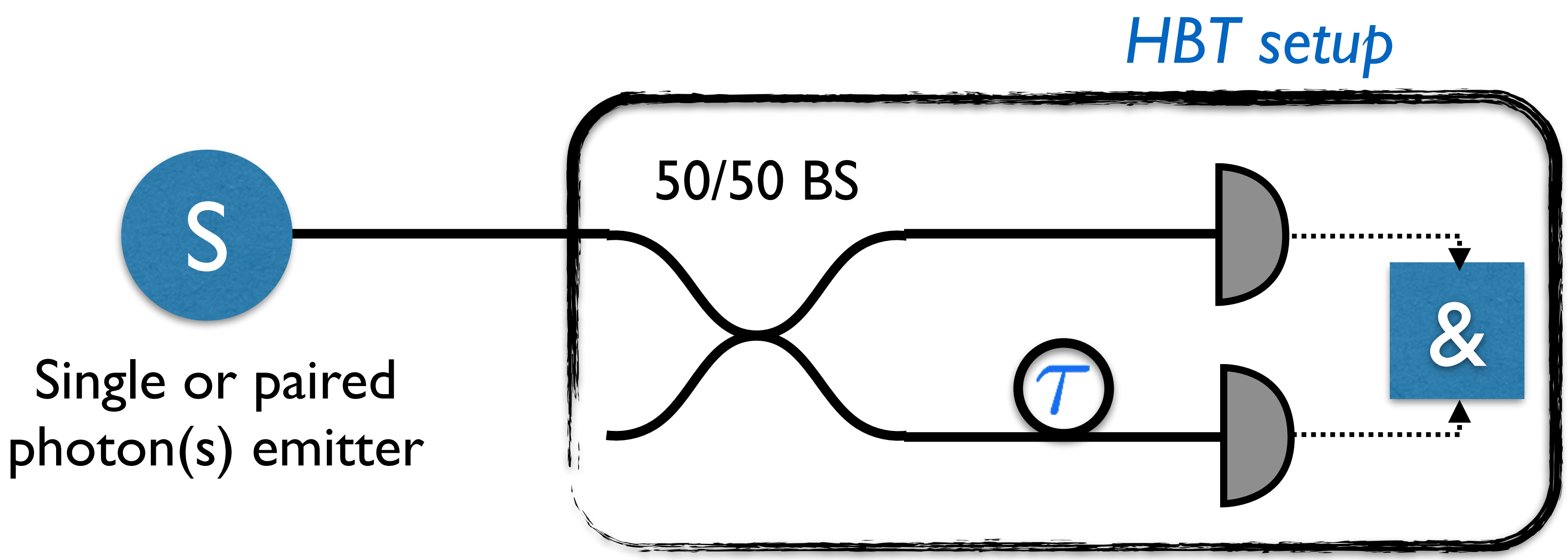

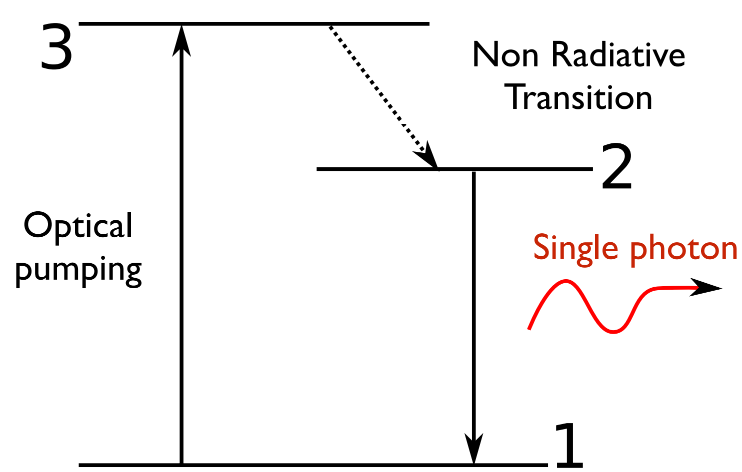

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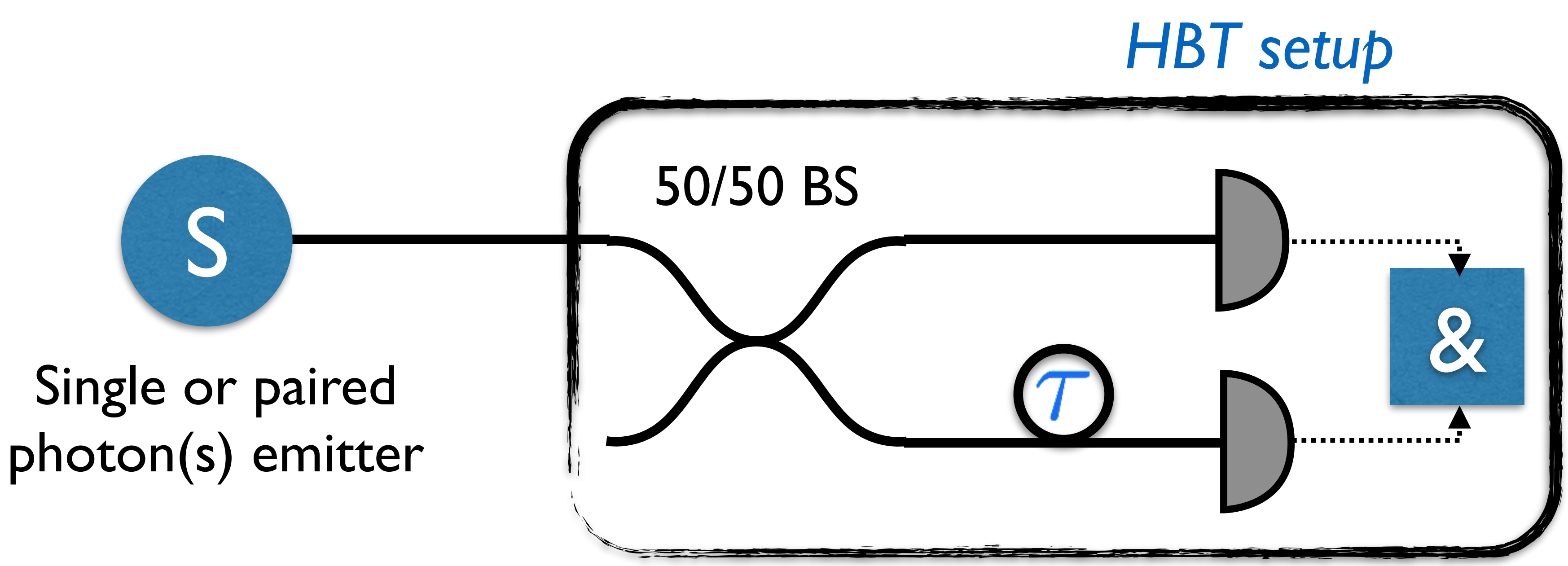

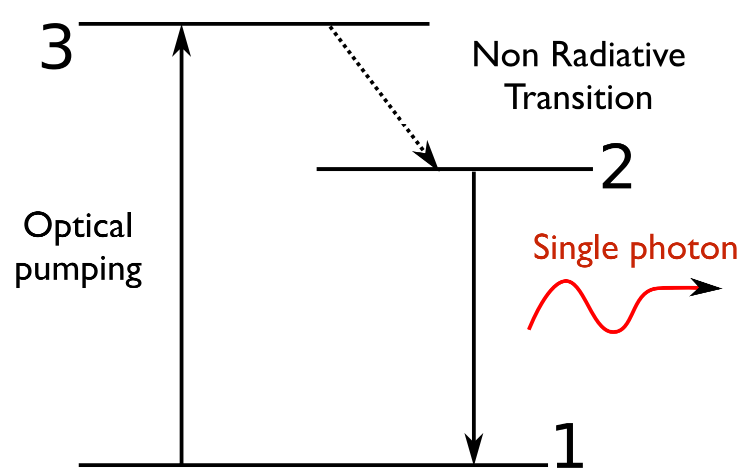

Relevant features

Efficiency	η	"Poissonization"
Dark counts	p_{dc}	noise level
Timing jitter	τ_d	resolution

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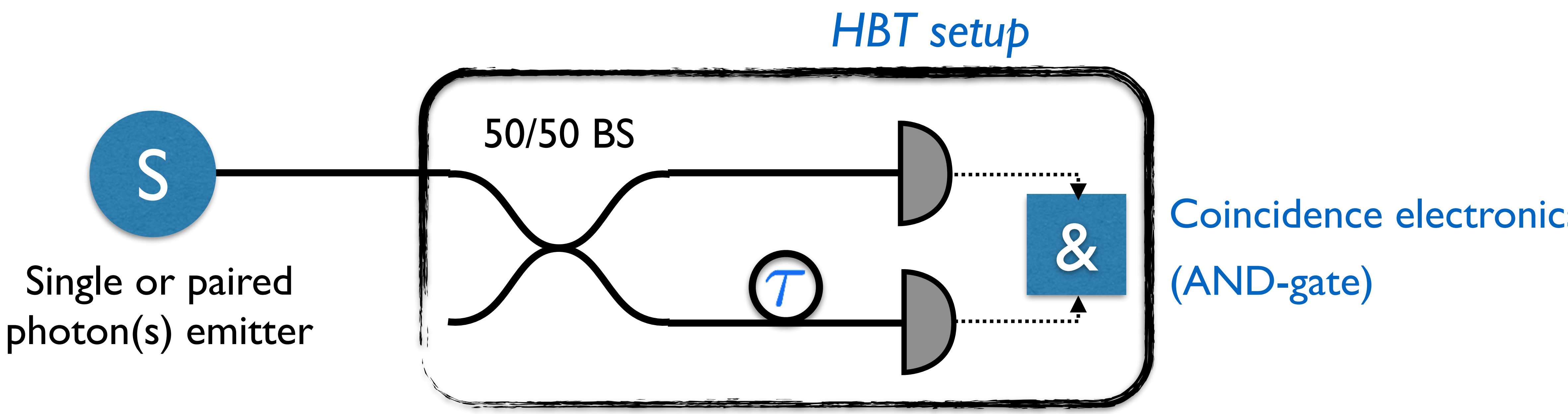

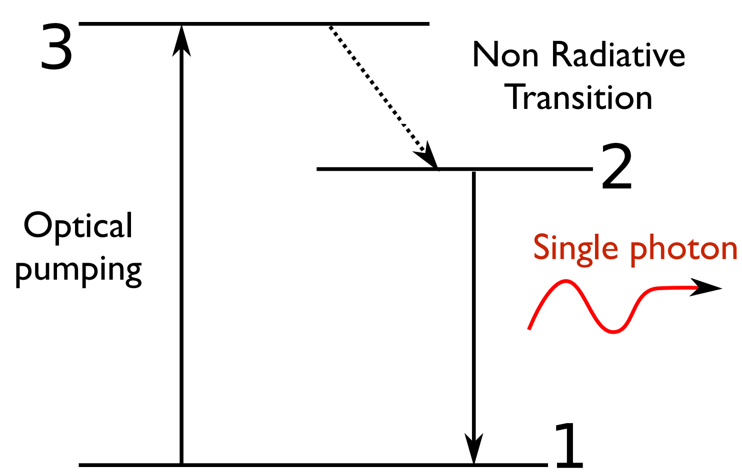

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- **Single mode operation**

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with $\widehat{n} = a^{\dagger}a$ photon number operator

$\langle \widehat{n}\rangle$ mean number of photons in the mode

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→ no correlation between subsequent photo-detections
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with Ω the pump rate driving the transition, and Γ^{-1} the lifetime of the excited state

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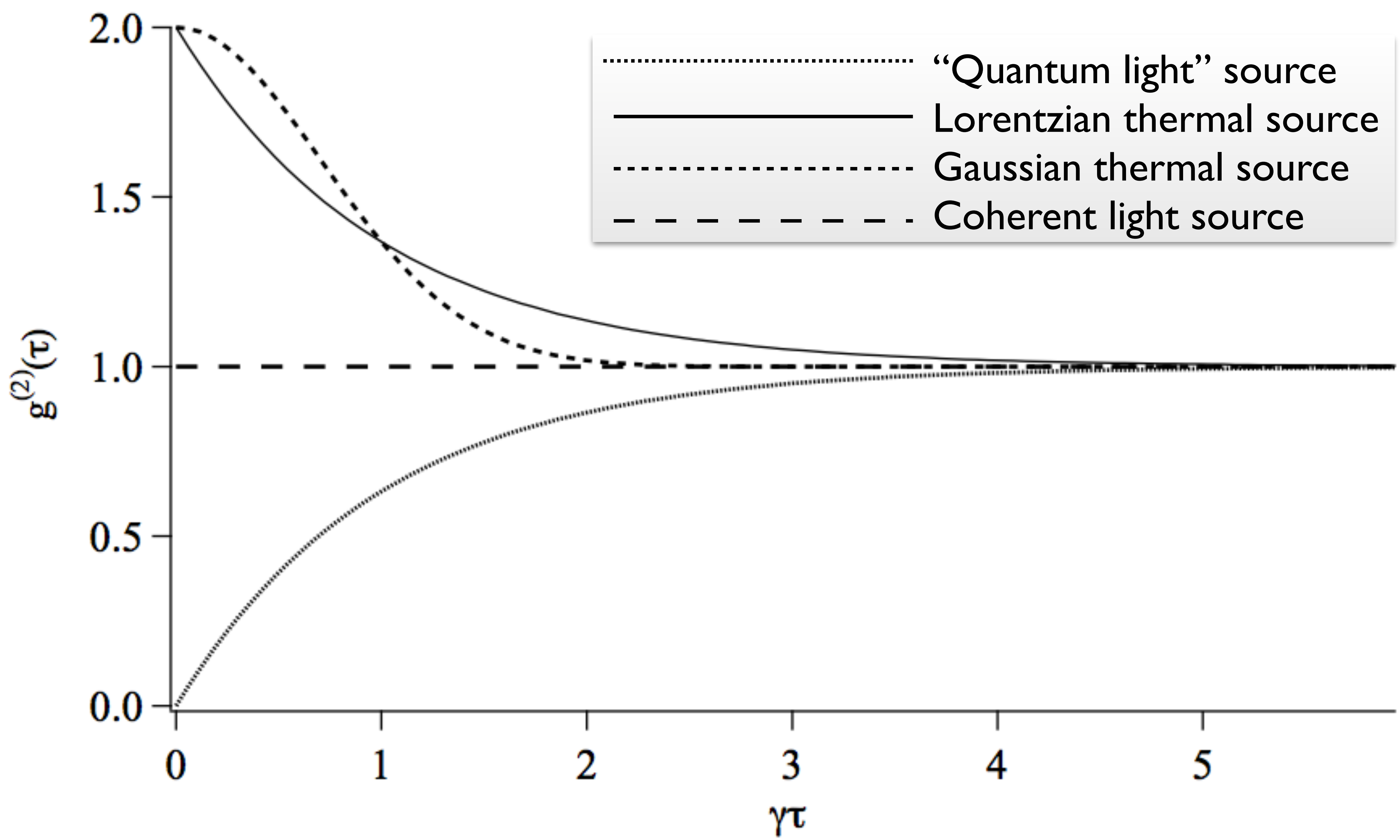
$$\rightarrow \begin{cases} g^{(2)}(0) & = & 0 \\ g^{(2)}(0) & \leq & g^{(2)}(\tau) \end{cases}$$

safe !

1.3 Little summary



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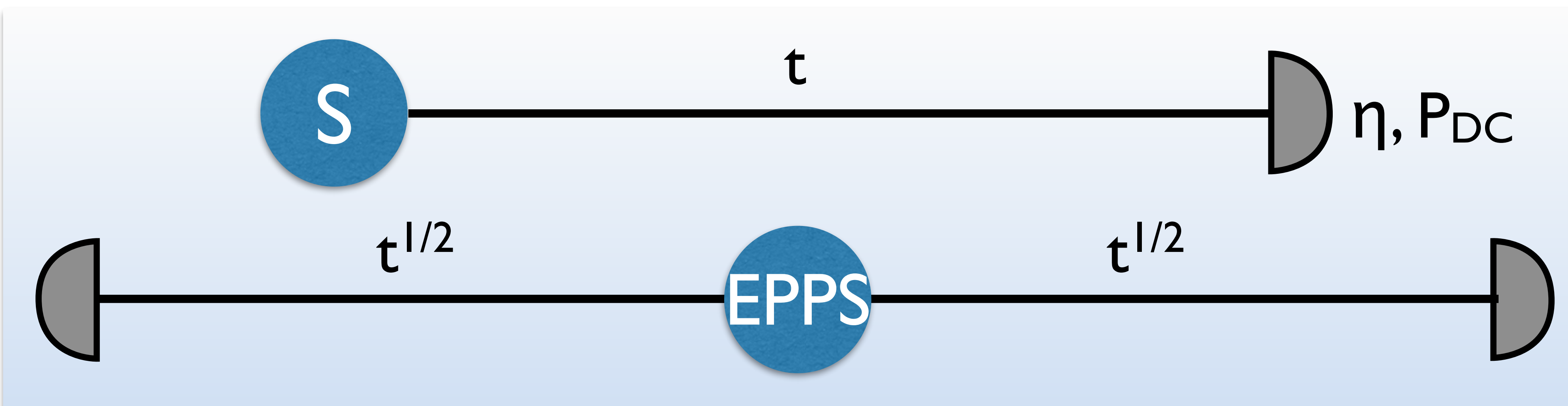

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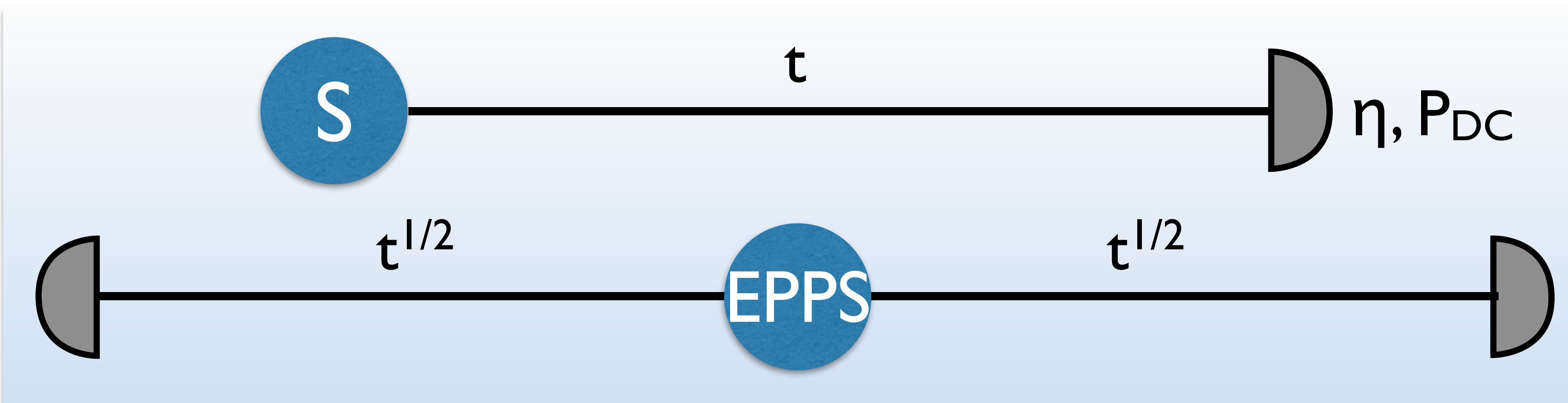
- **The context of today's quantum communication**

Distribution of quantum bits of information
using single photon and entangled photon pair sources



- **Application to quantum key distribution (QKD)**

Single photon (pair) emission character ➜ security condition

1.2 HBT in quantum optics

- **The context of today's quantum communication**

  Distribution of quantum bits of information
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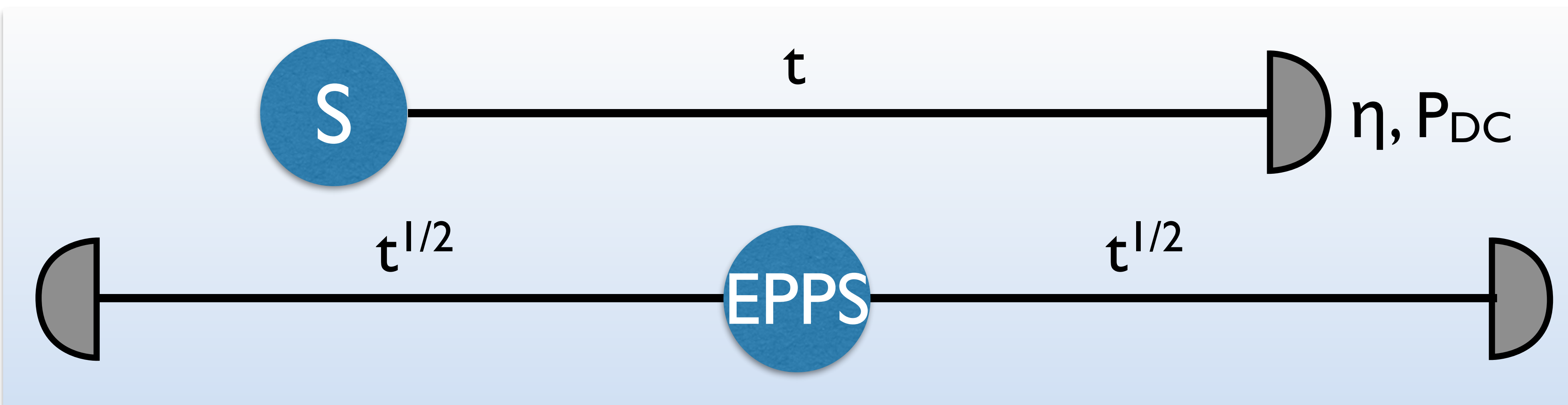

- **Application to quantum key distribution (QKD)**

  Single photon (pair) emission character ➜ security condition

  HBT: an experimental resource for characterization

  ➜ Sources' emission statistics: Poissonnian, Thermal (Bose-Einstein)

  ➜ Photons' coherence time

Outline

1. **Introduction**
2. **HBT for characterizing single photon sources (SPS)**
   1. What is an SPS ?
   2. “True” single photon sources (NV-centers, Qdots)
   3. Heralded single photon sources (HSPS)
   4. Connecting HSPSs in a quantum network
3. **HBT for characterizing photon pair sources**

2.1 Single photon sources

- **What is a single photon source ?**

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P0: prob. of having no photon at all
P1: prob. of having exactly 1 photon
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- **Different types of single photon sources (SPS)**

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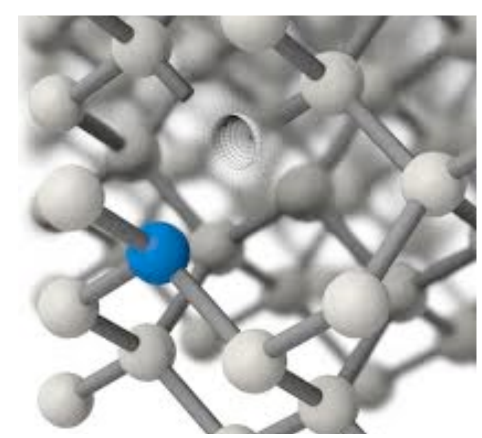
Different types of single photon sources (SPS)

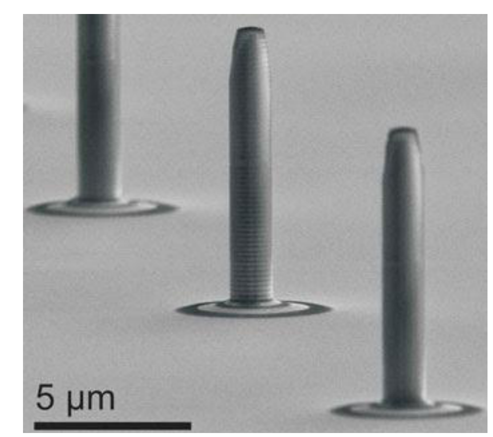
Molecule
Semiconductor devices
NV center in diamond
Isolated ion/atom

➜ Any 2 energy-level isolated system

NV centers in diamond



Q-dots



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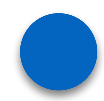

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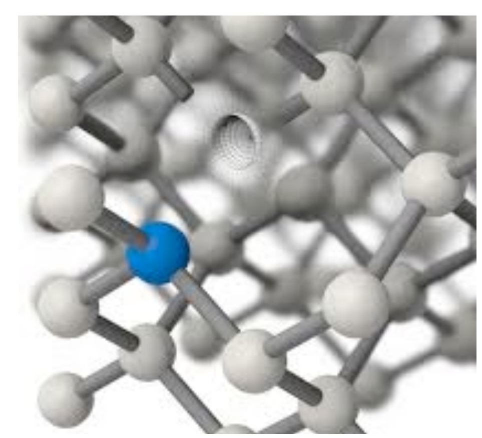

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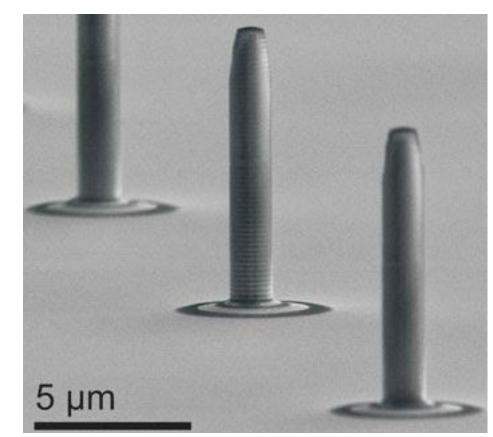

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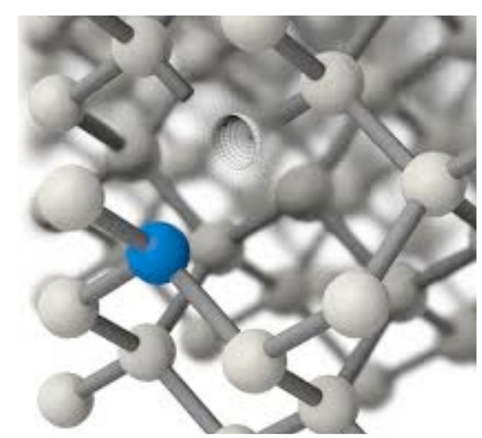

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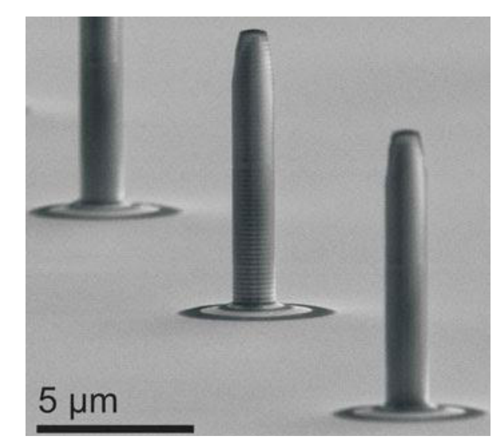

What are they used for ?

Quantum cryptography (QKD)

Fundamental tests in quantum physics (Wheeler's delayed-choice exp.)

(Quantum) metrology (phase measurements, magnetometry, etc.)

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2.2 True SPS based on a single NV center in diamond

- **Confocal microscopy based setup**

[Wrachtrup's group, Stuttgart] P. Siyushev *et al.*, New J. Phys. **11**, 113029 (2009)

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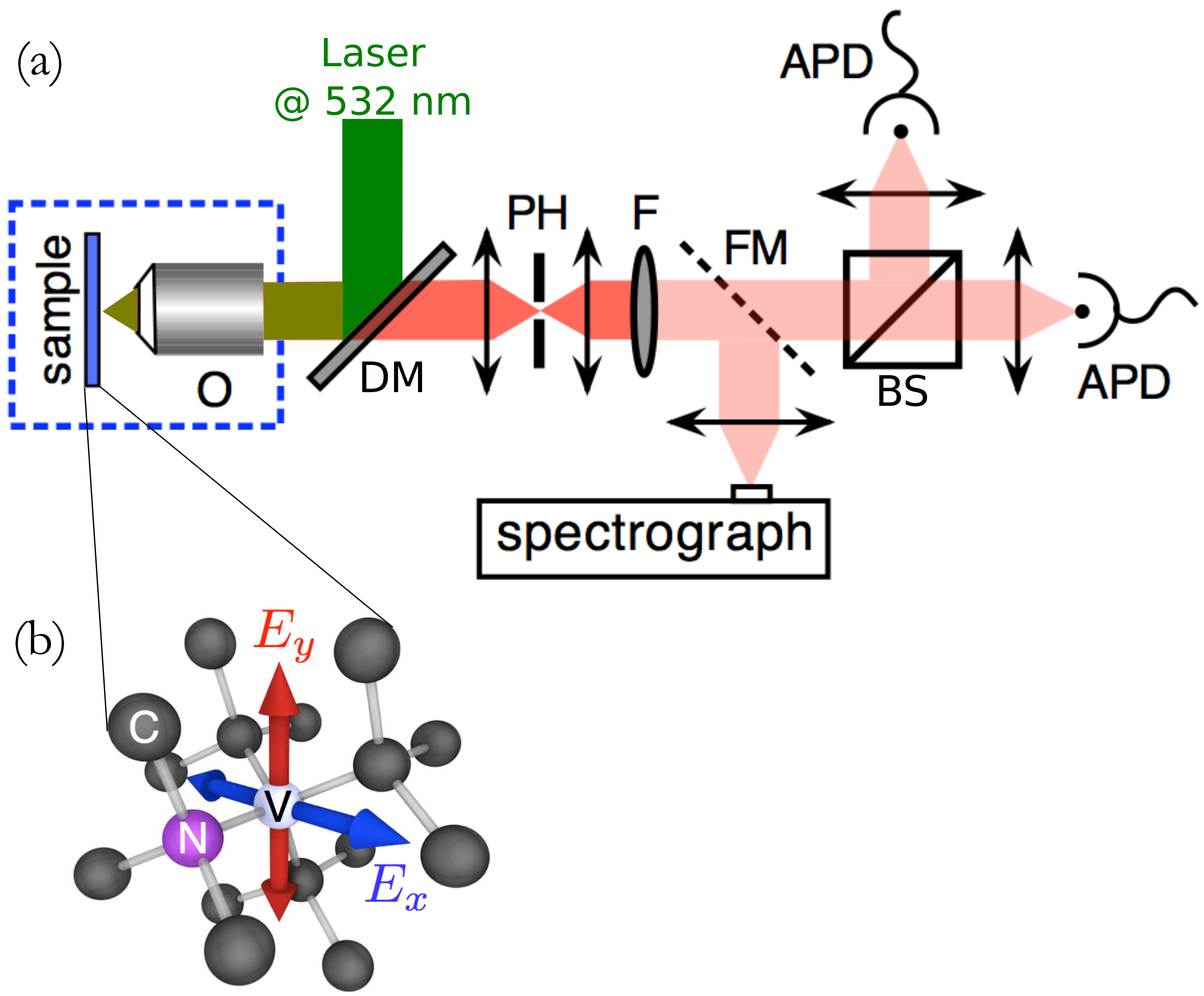

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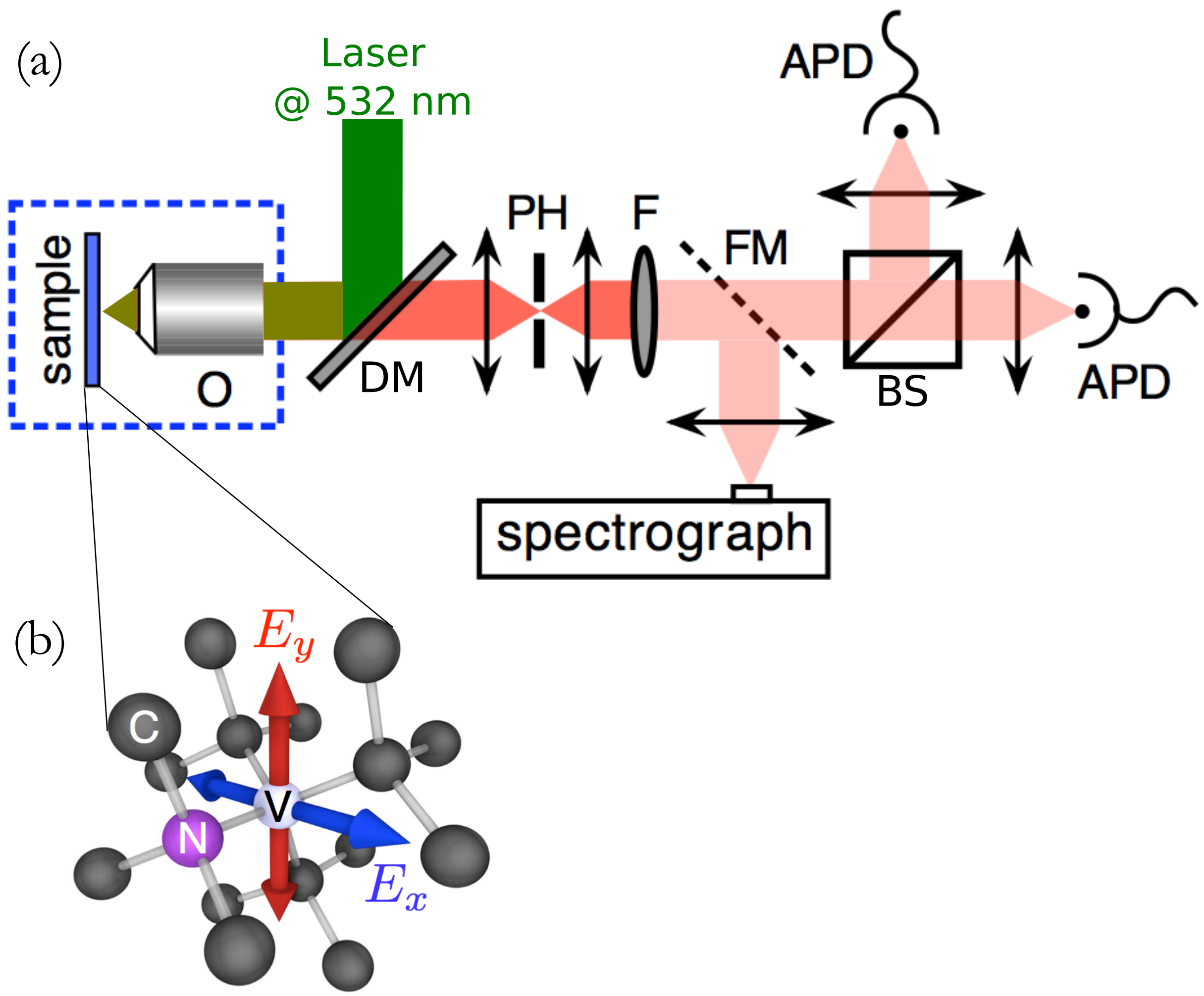
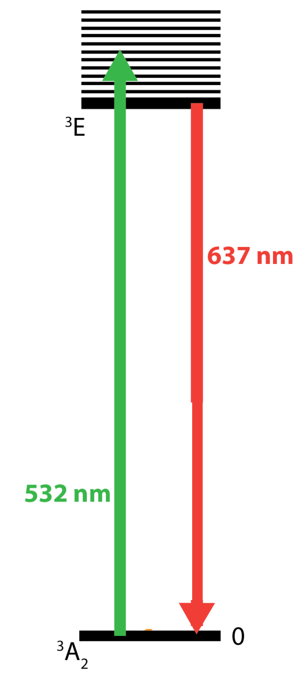


- "Artificial atom" energy levels



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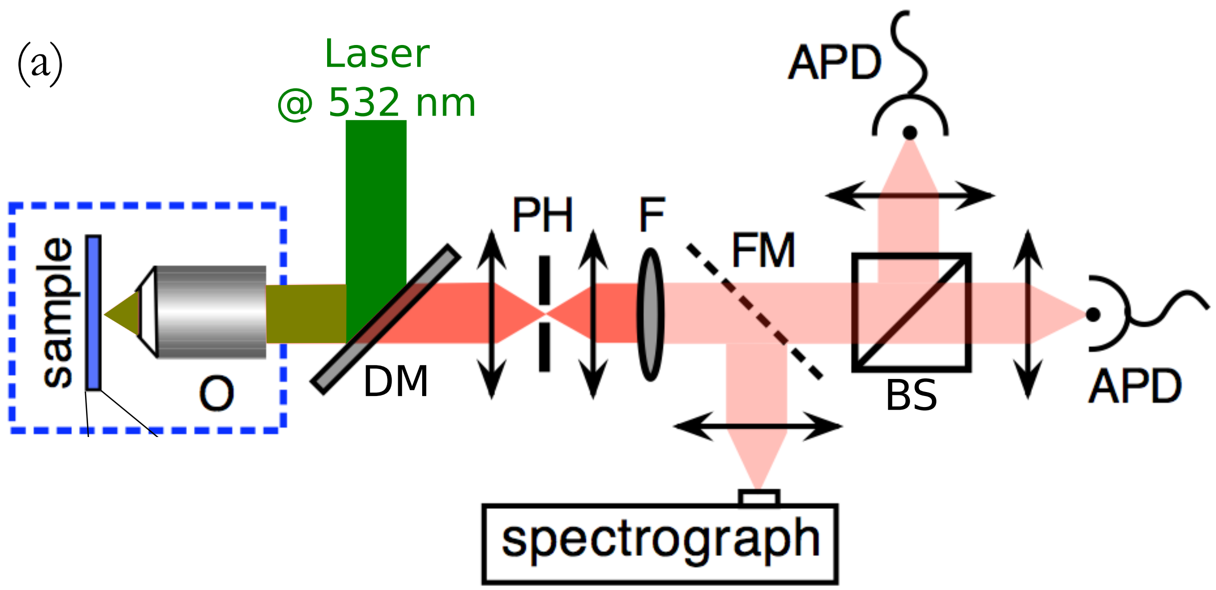

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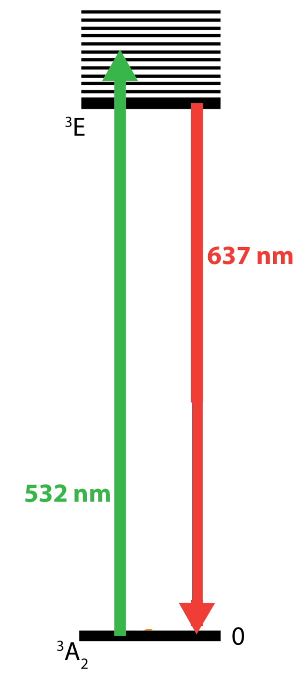

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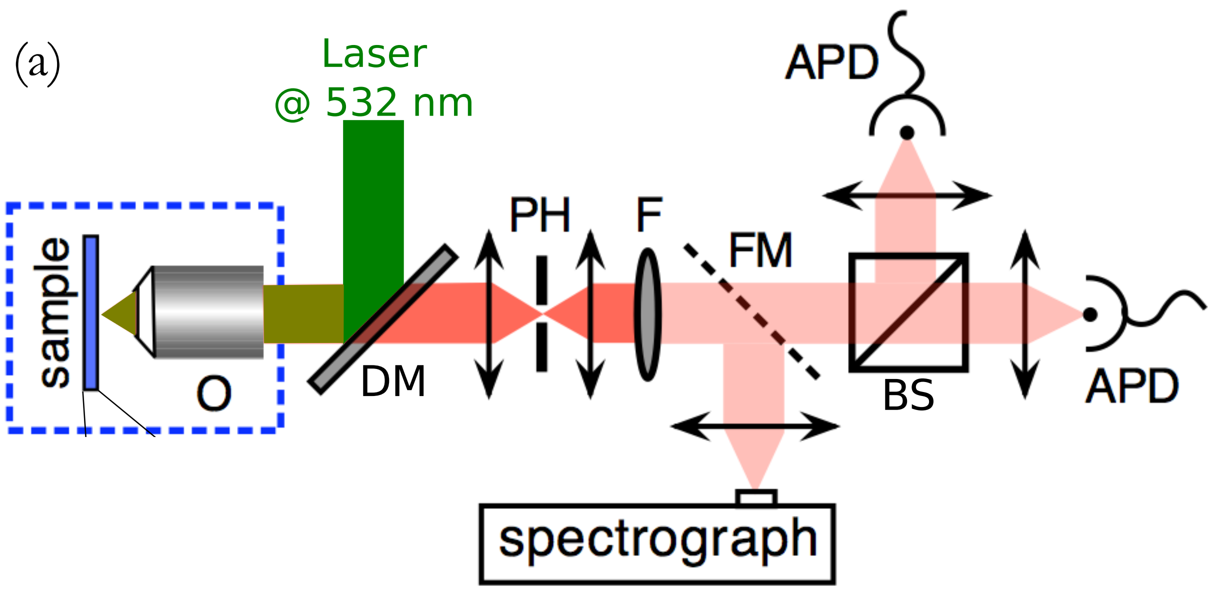

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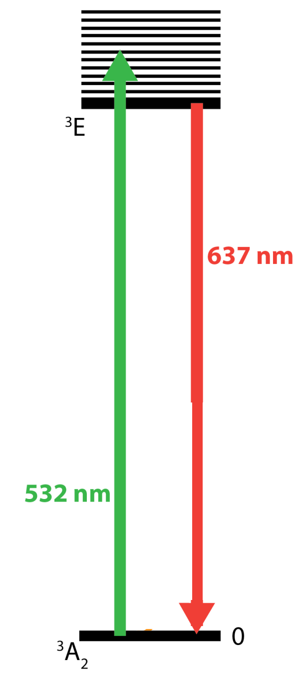

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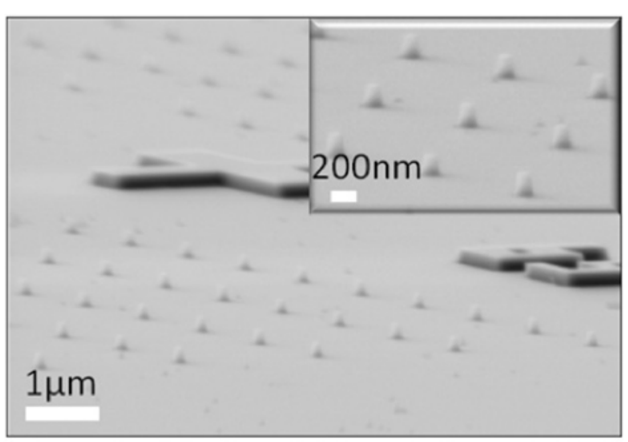

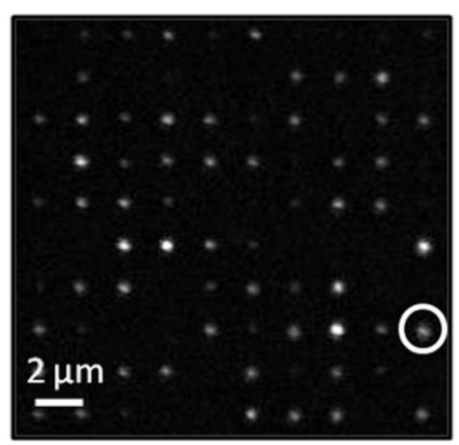

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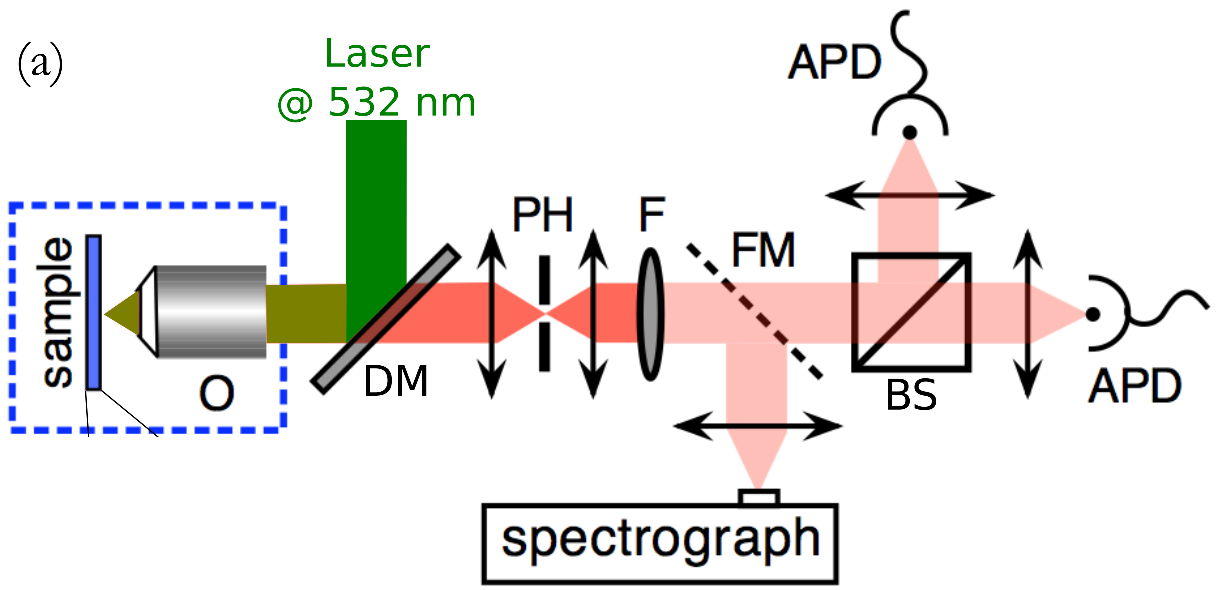

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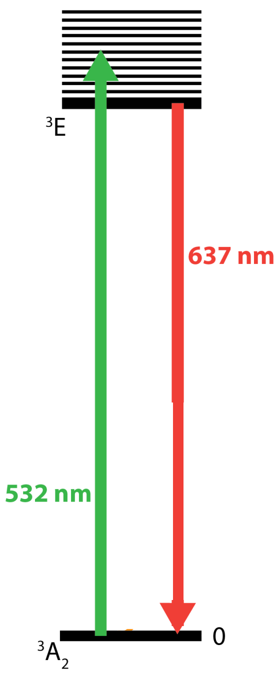

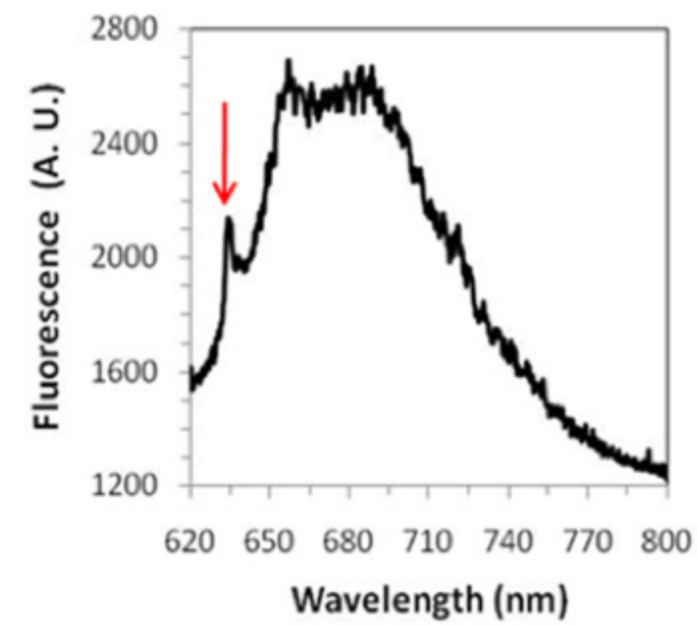

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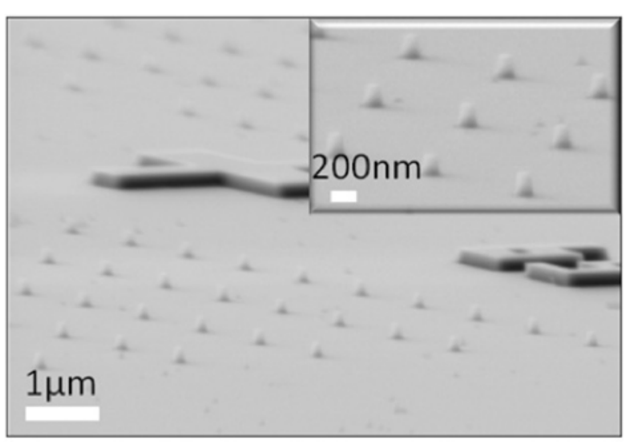

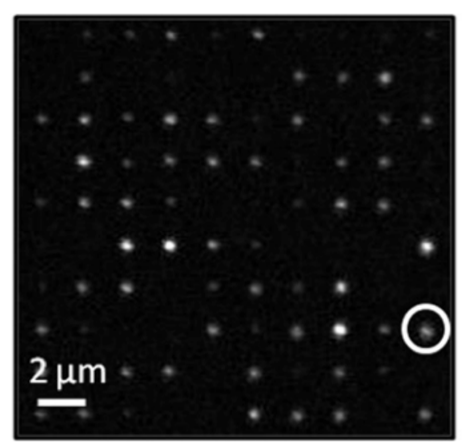

Zero photon line

[Wrachtrup's group, Stuttgart] P. Siyushev *et al.*, New J. Phys. **11**, 113029 (2009)
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Antibunching measurements

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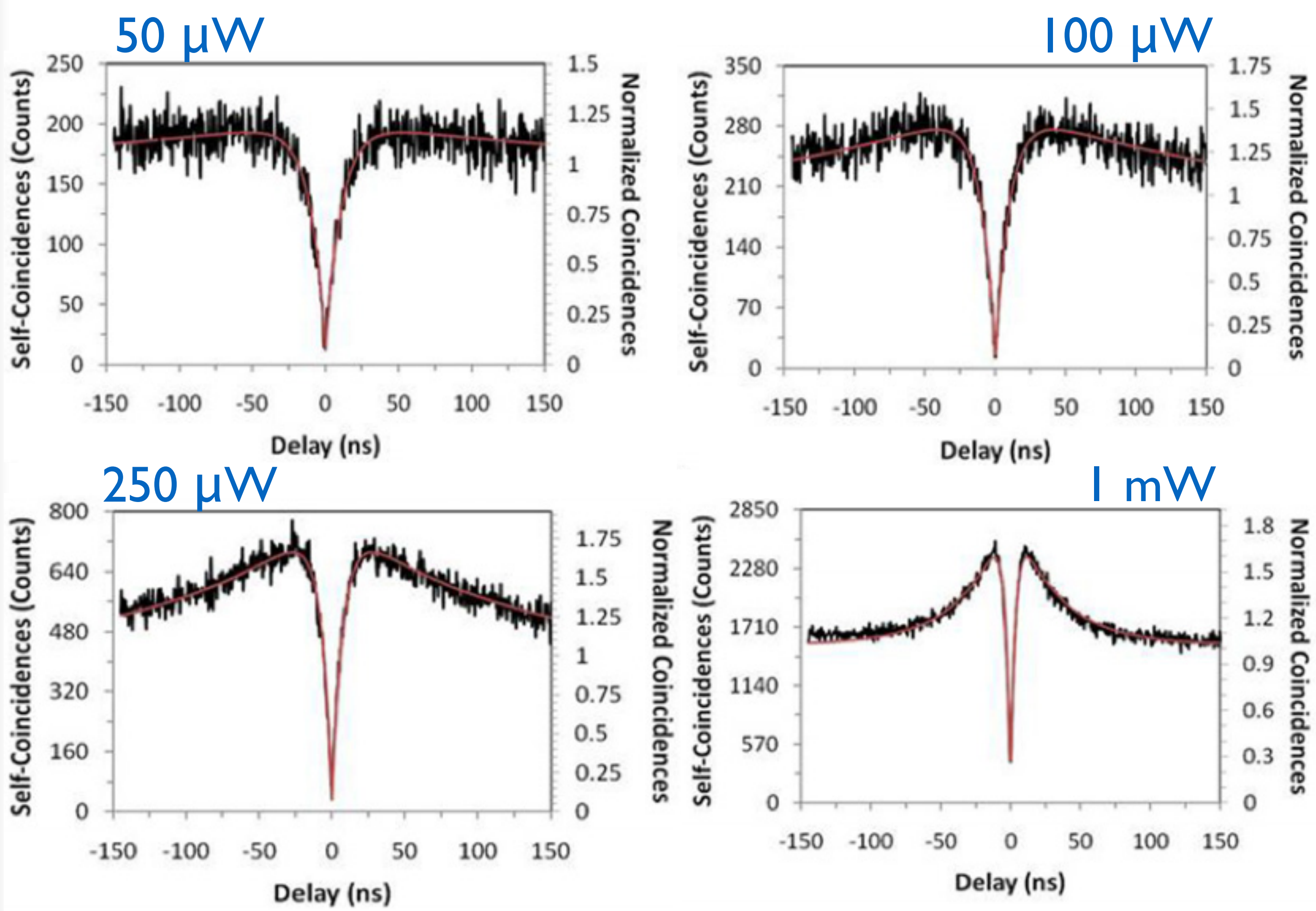

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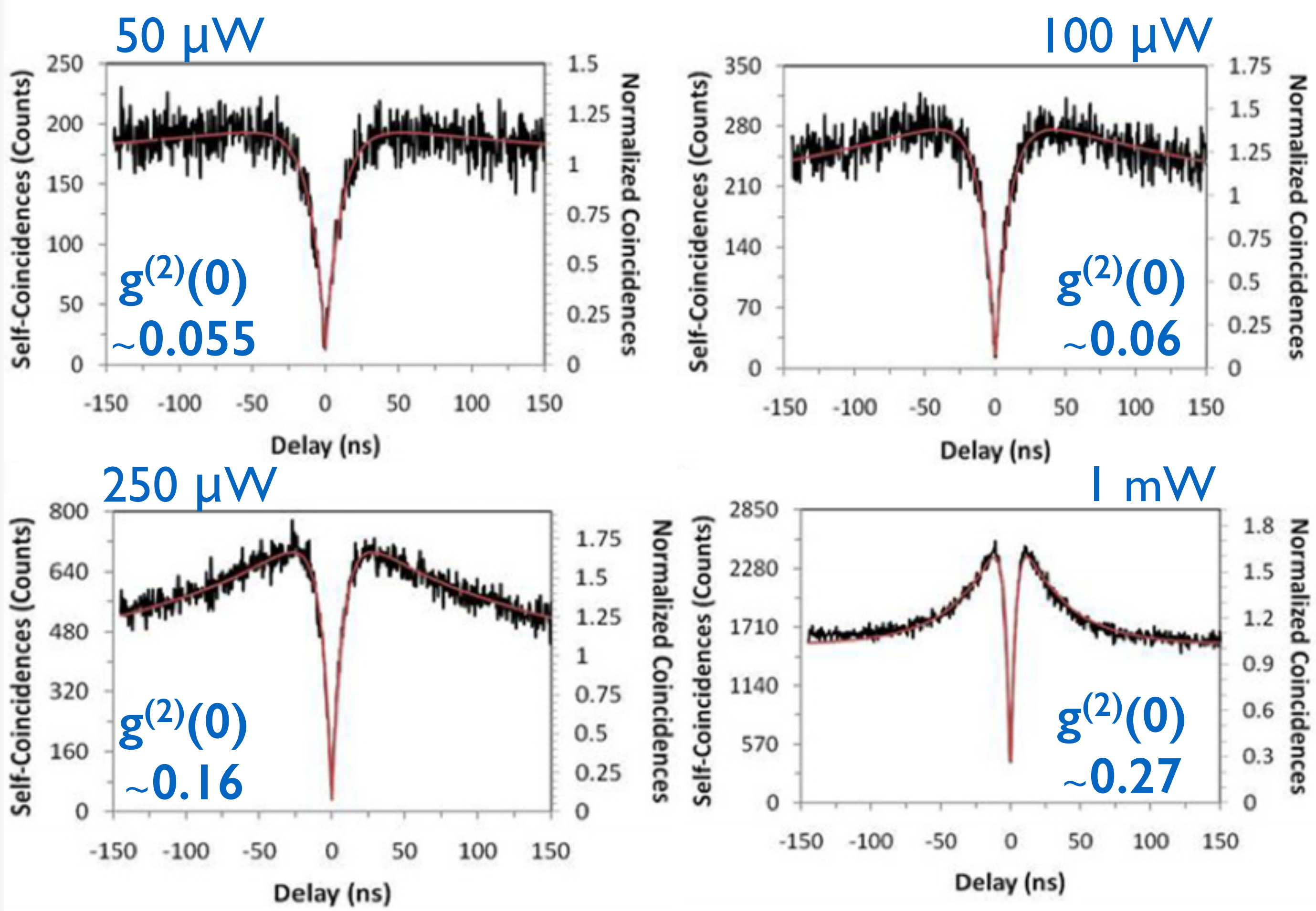

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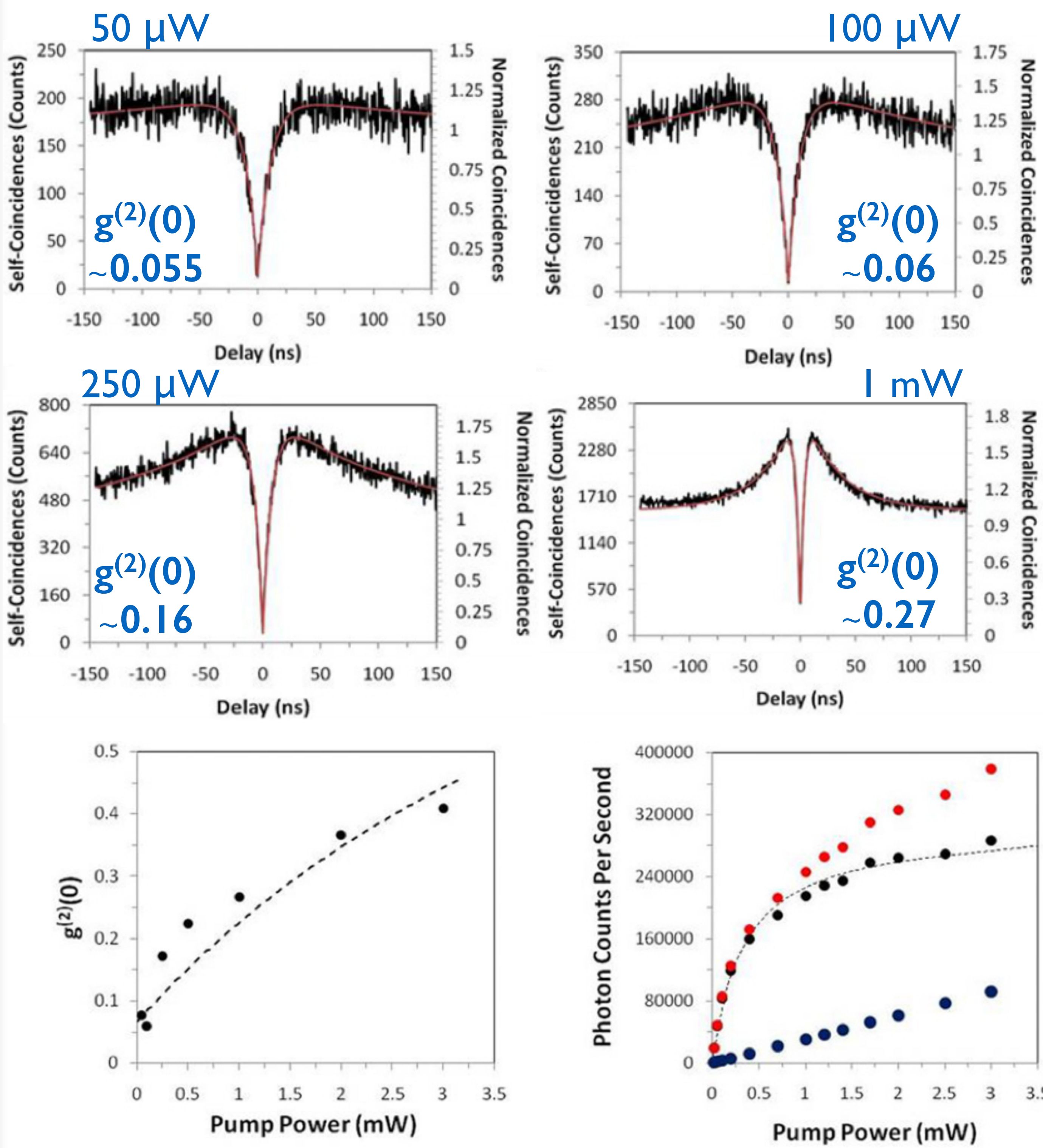

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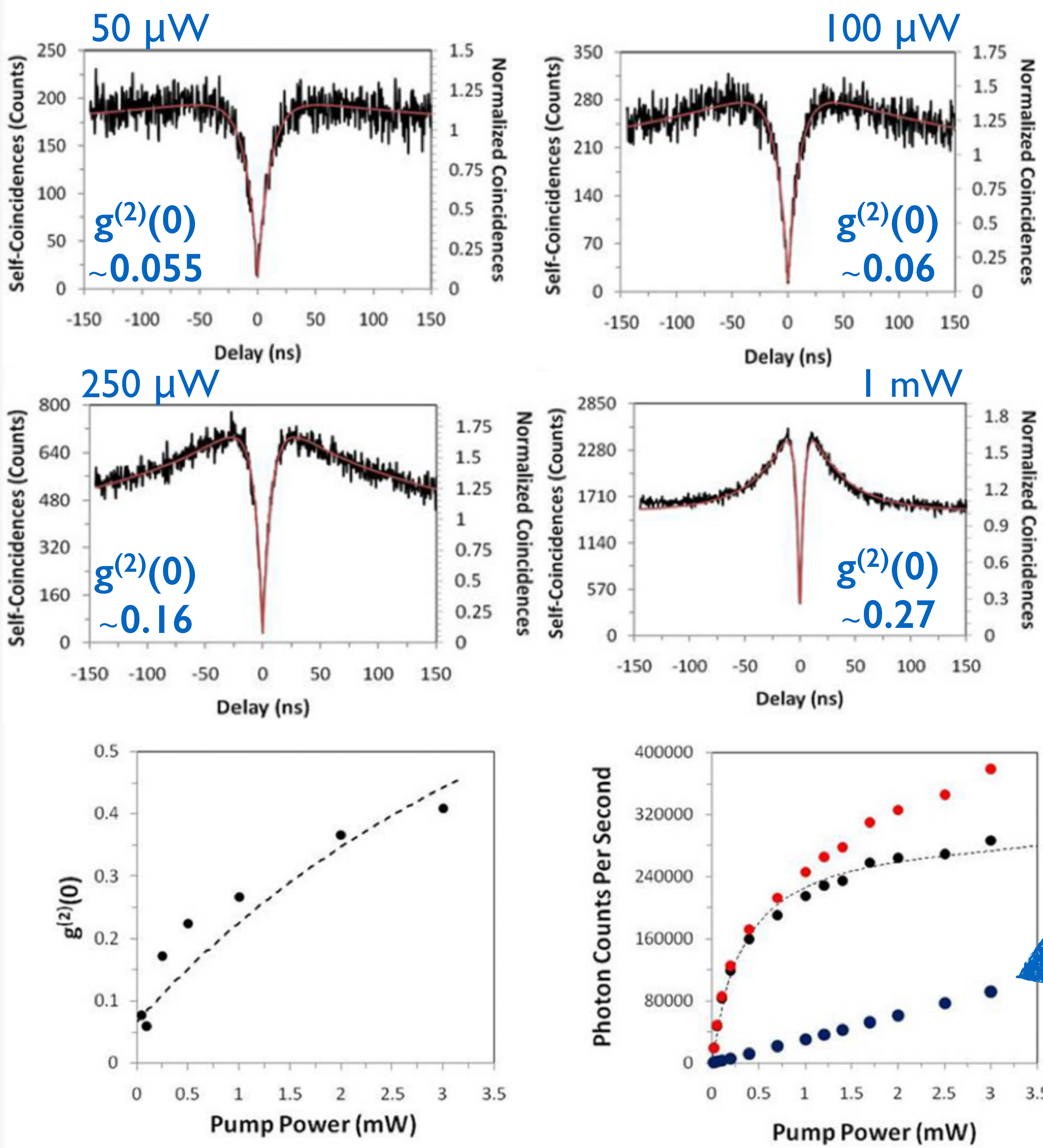

Poissonnian background photons

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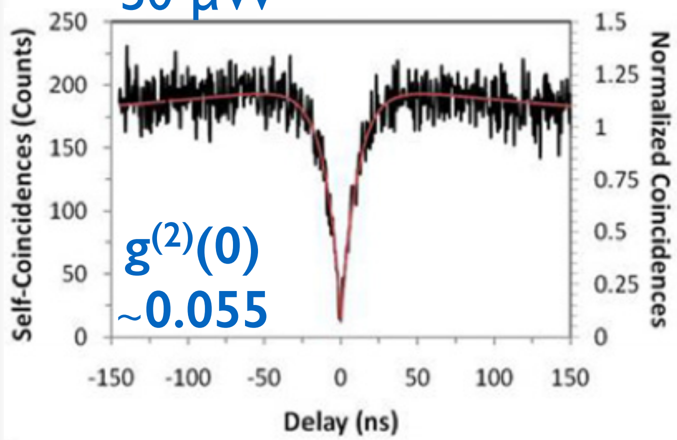
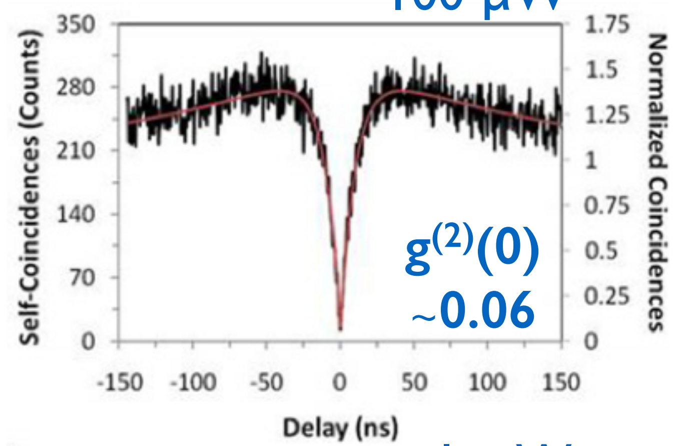
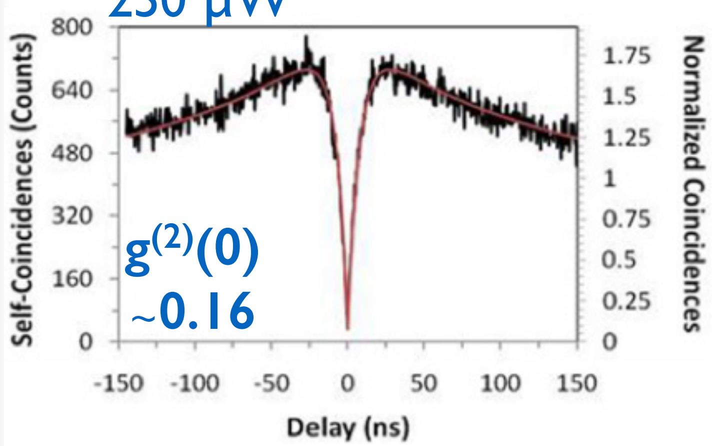
50 µW



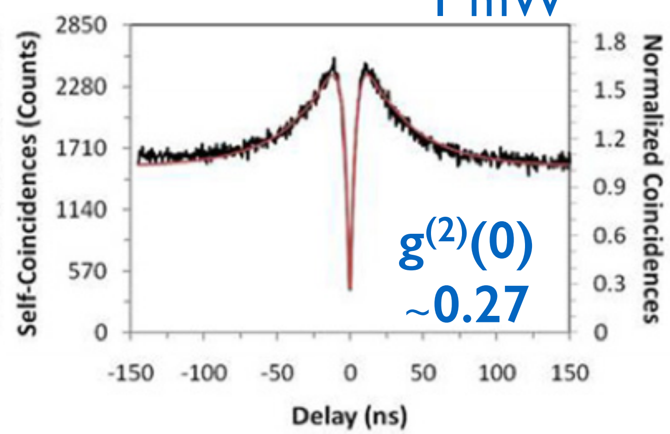
100 µW



250 µW

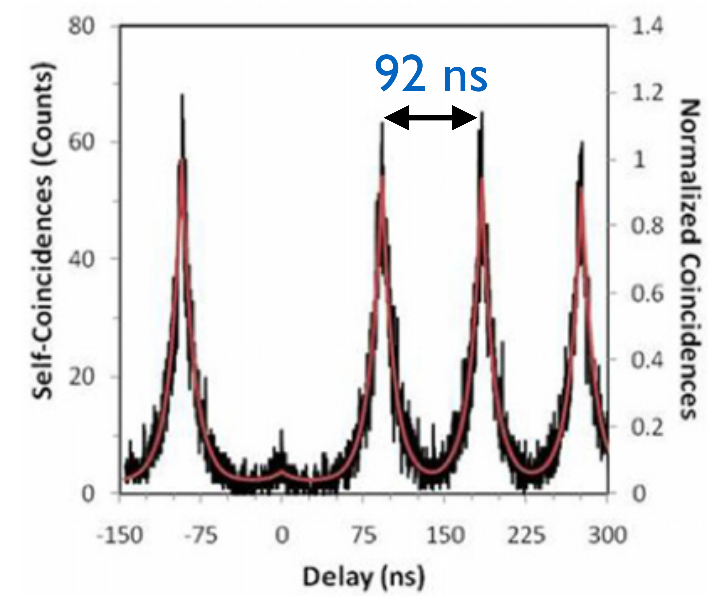


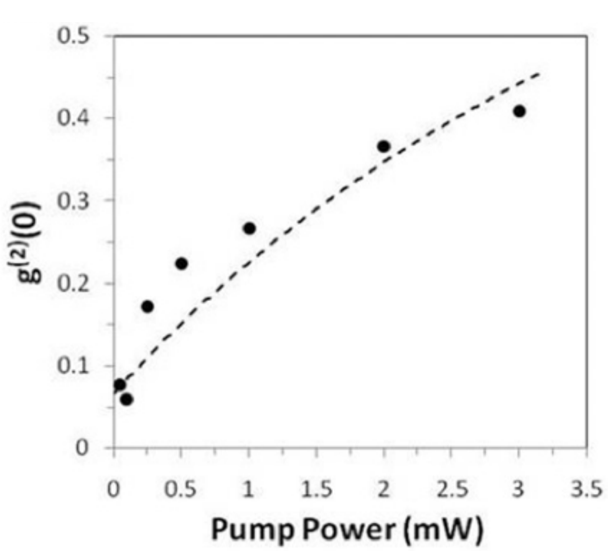
1 mW

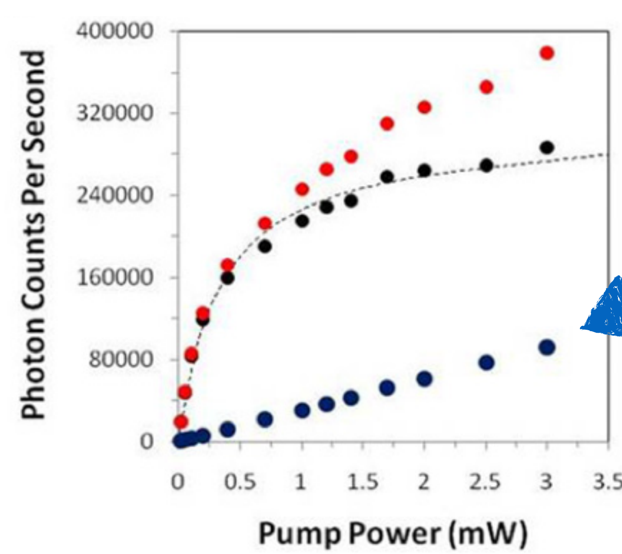


Pulsed excitation

<65> µW ➜ $g^{(2)}(0)$~0.16







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- **Many (many) types and fab. processes**

[Vuckovic's group, Stanford] J. Vuckovic *et al.*, Rep. Prog. Phys. **75** 126503 (2012) **[Review]**

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➜ an entire zoology of properties

Material system	λ (nm)	Tmax (K)
InAs/GaAS	~850 - 1000	50
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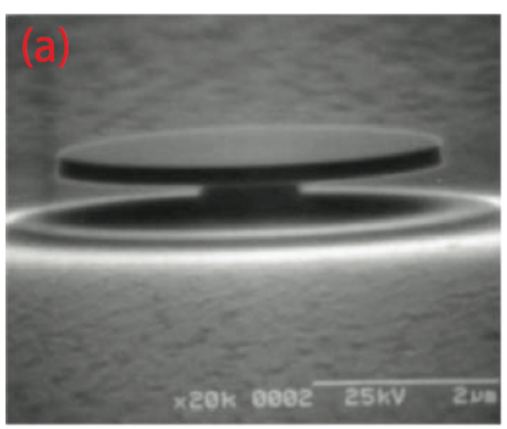
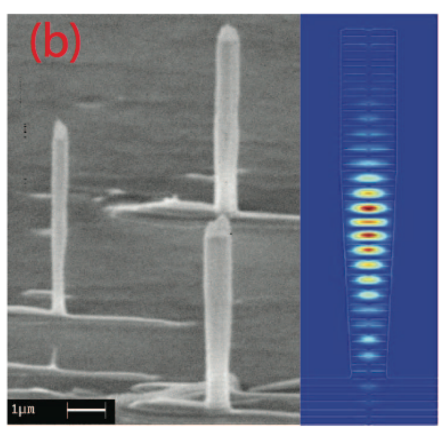
- **Surrounded by a cavity and search for the single exciton line (X-polarized)**

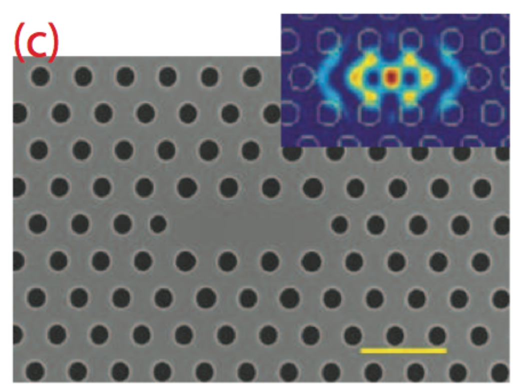
μ-disk



μ-pillar



photonic Xtal



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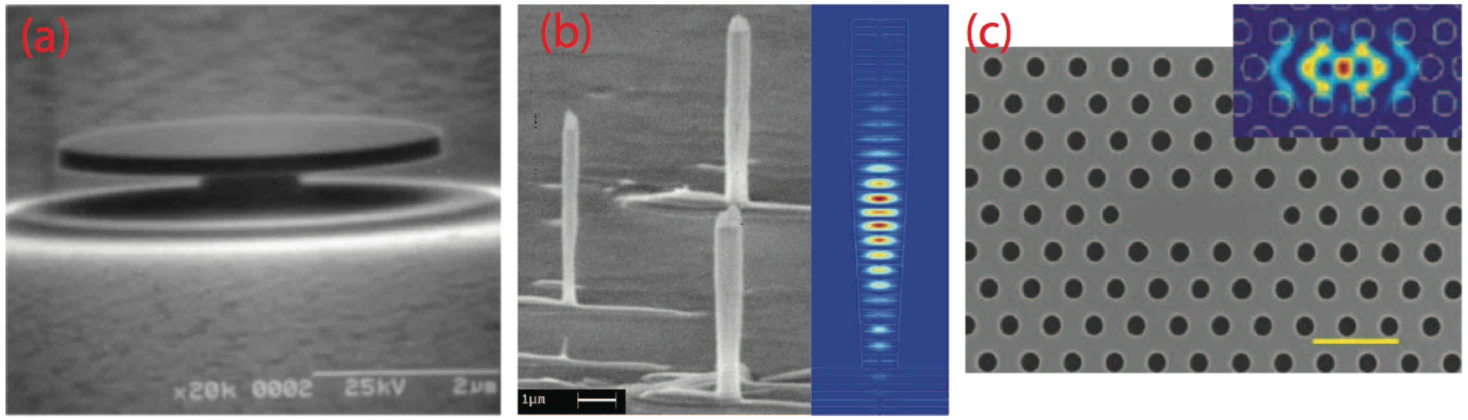

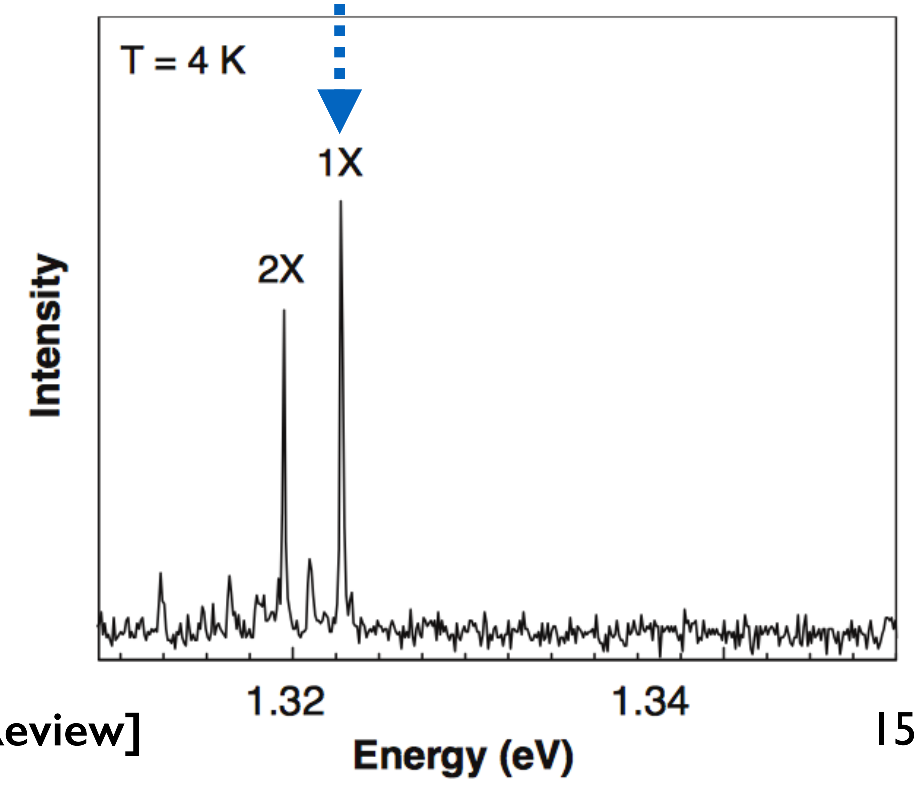

[Imamoglu's group, ETH] C. Becher *et al.*, Physica E **13**, 412 (2002)
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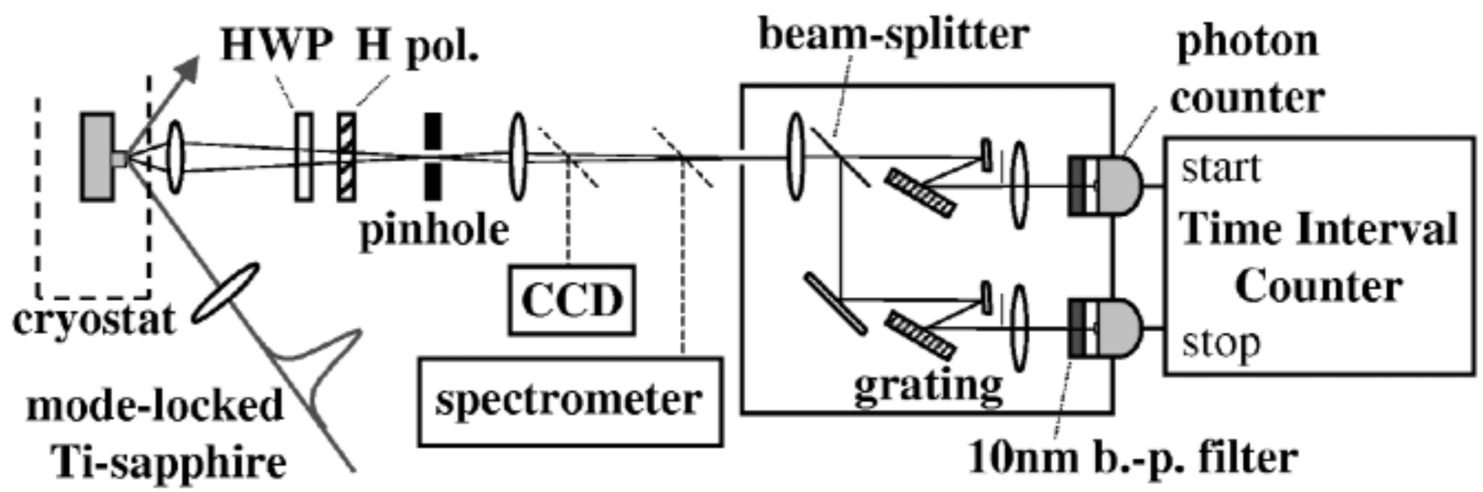

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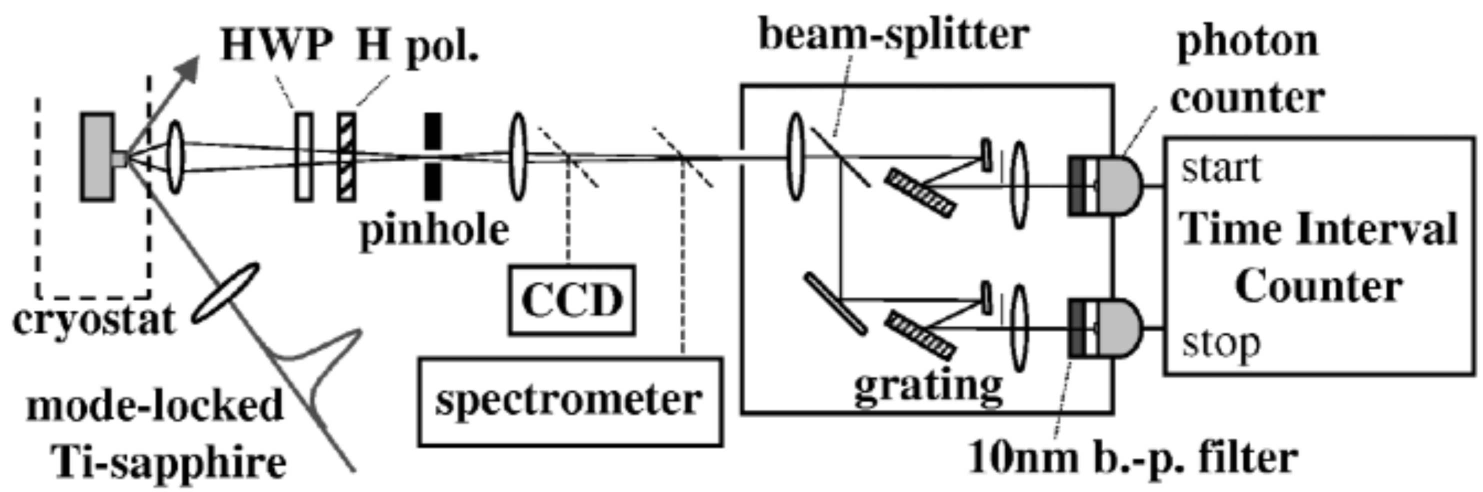
~ 4 - 50 K



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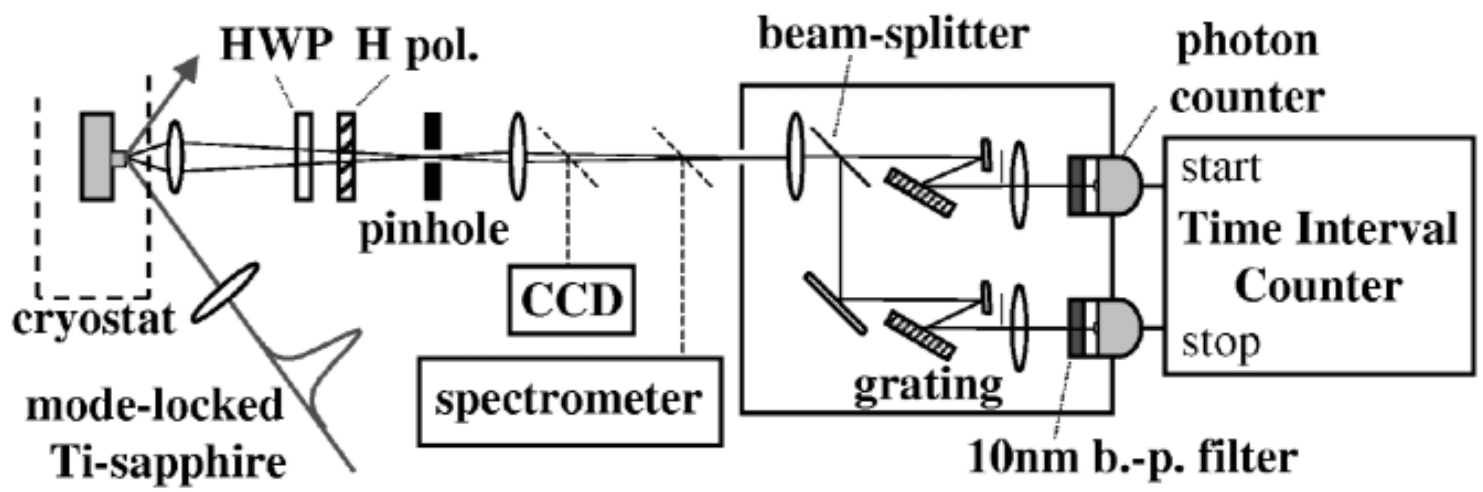

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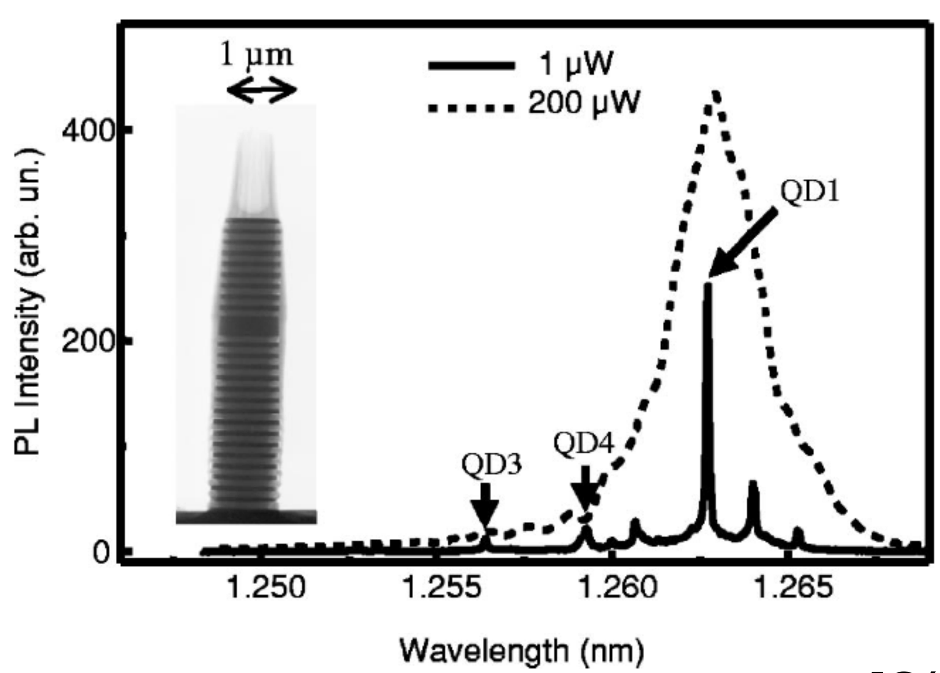

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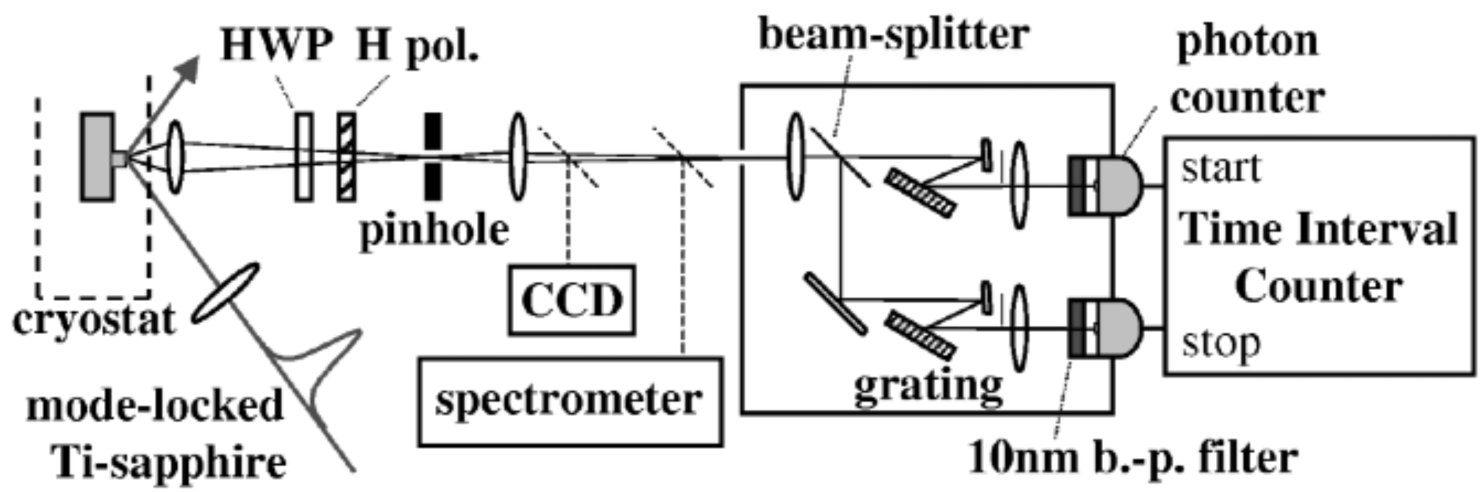

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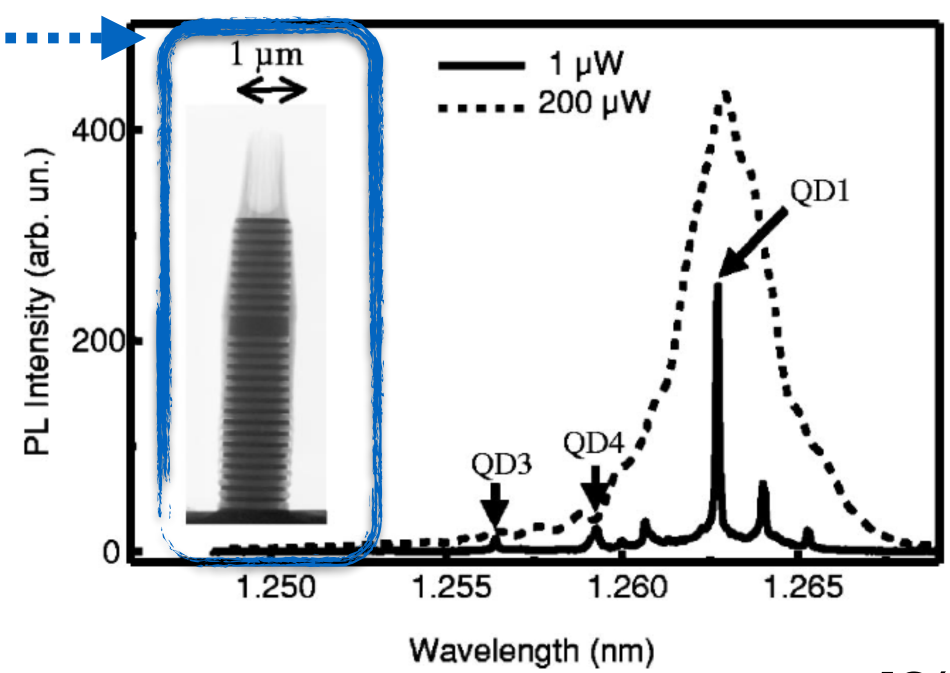

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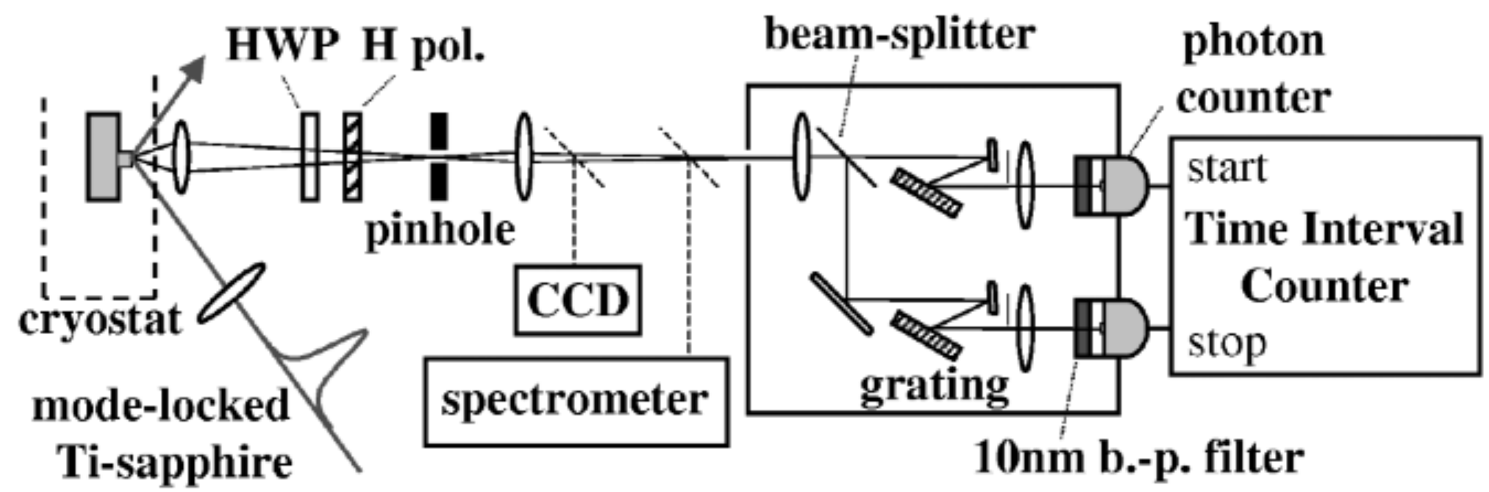

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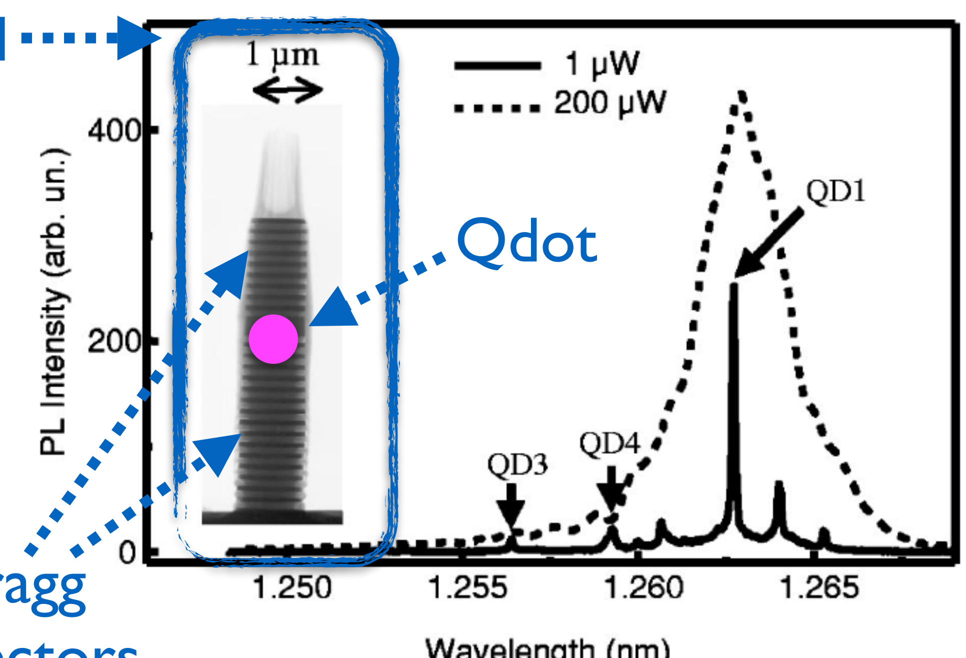

Bragg reflectors

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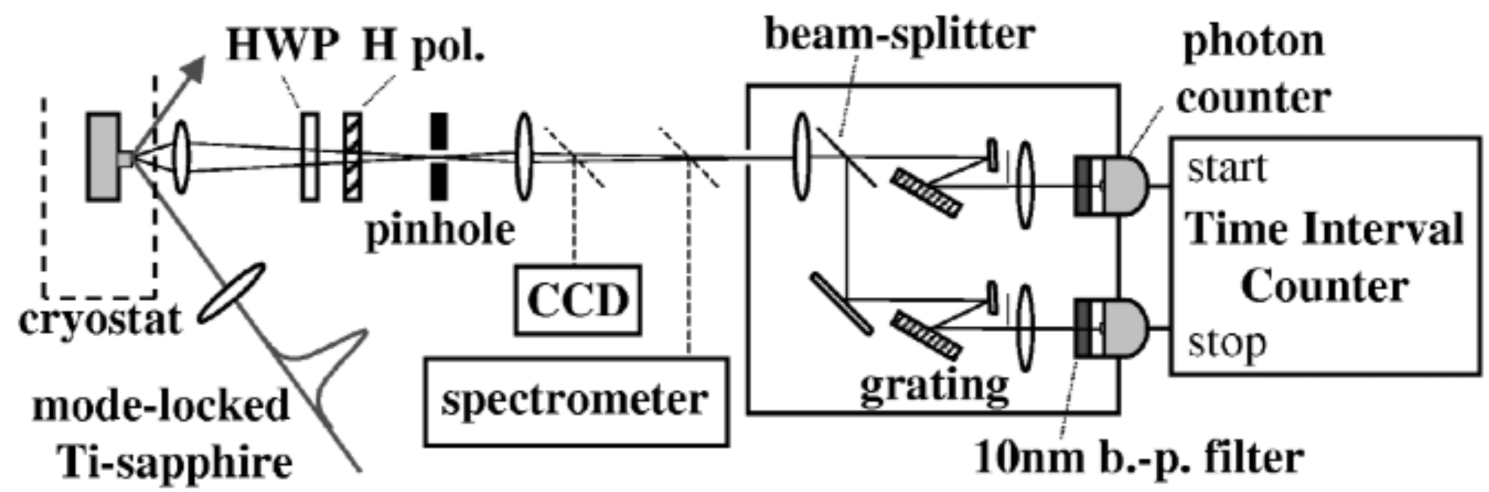
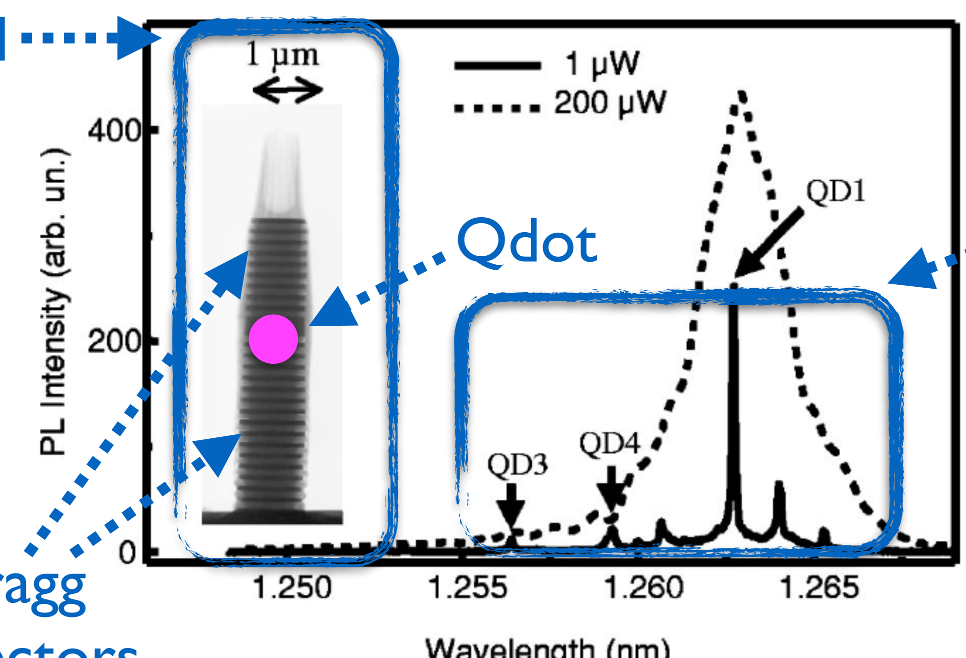


[Yamamoto's group, Stanford] C. Santori *et al.*, PRL **86**, 1502 (2001)

- **Weak vs strong excitation**

TEM



Bragg reflectors

A few sharp emission lines
➜ different Qdots having a single exciton
➜ so-called "X-line"

[Gérard's group, CEA] E. Moreau *et al.*, APL **79**, 2865 (2001)

2.2 True SPS based on a single quantum dot

Antibunching measurements

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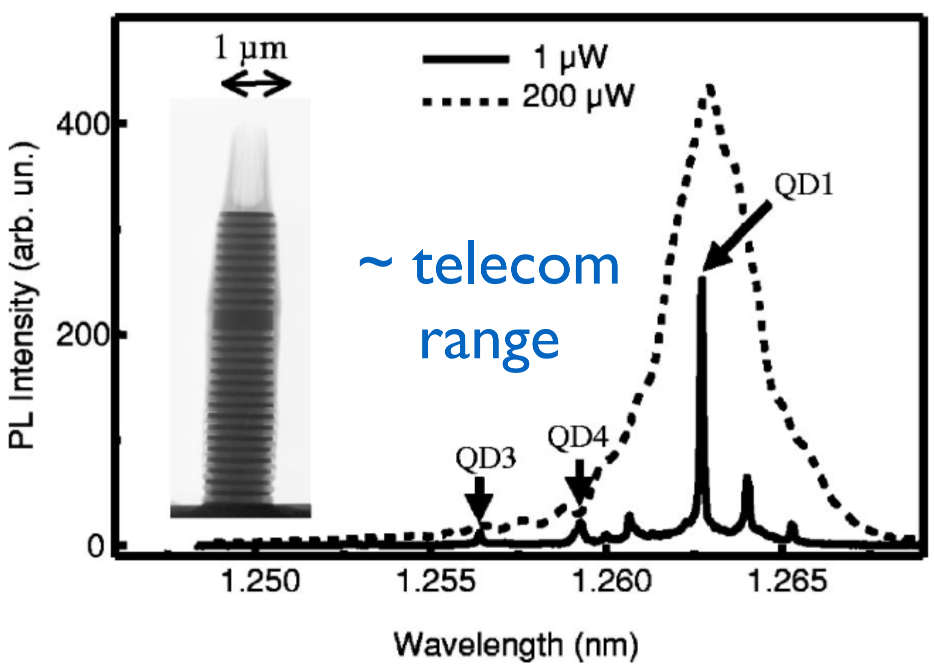

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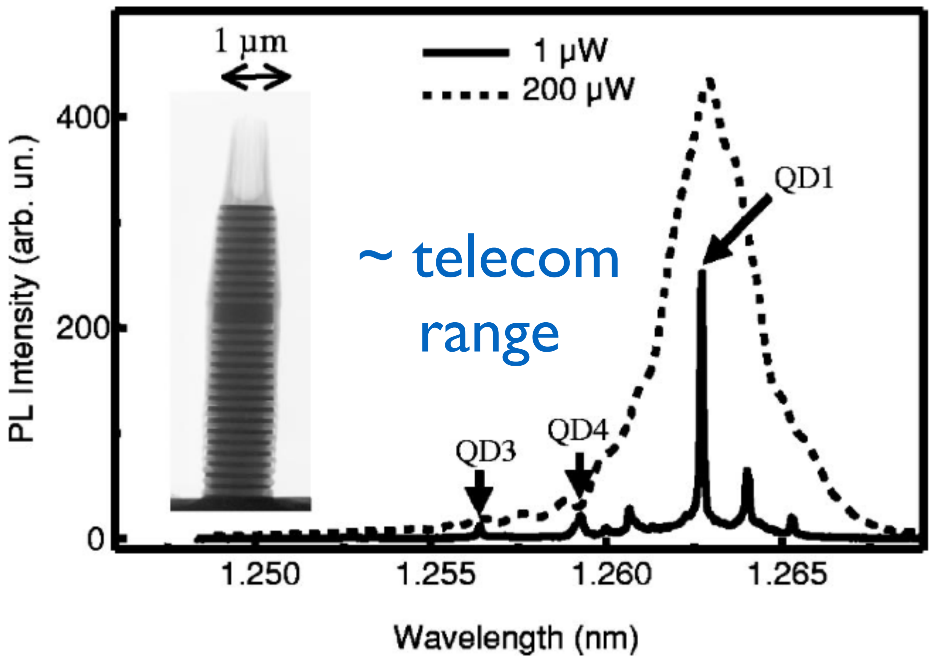
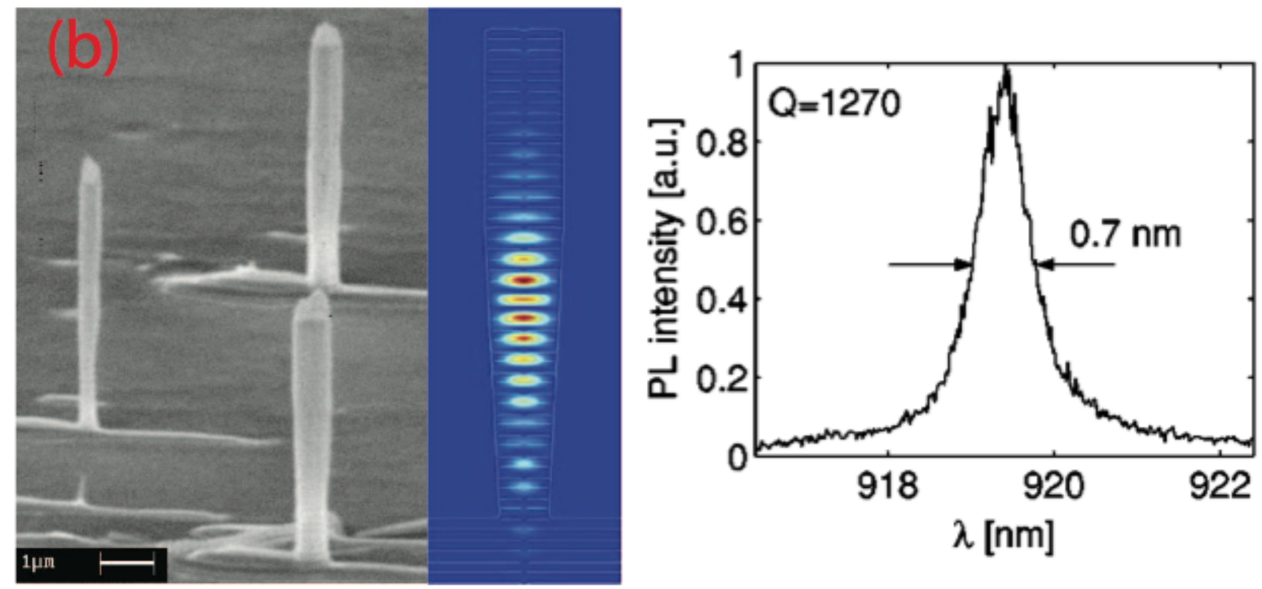


~ telecom range

In 2003, Vuckovic's group, Stanford



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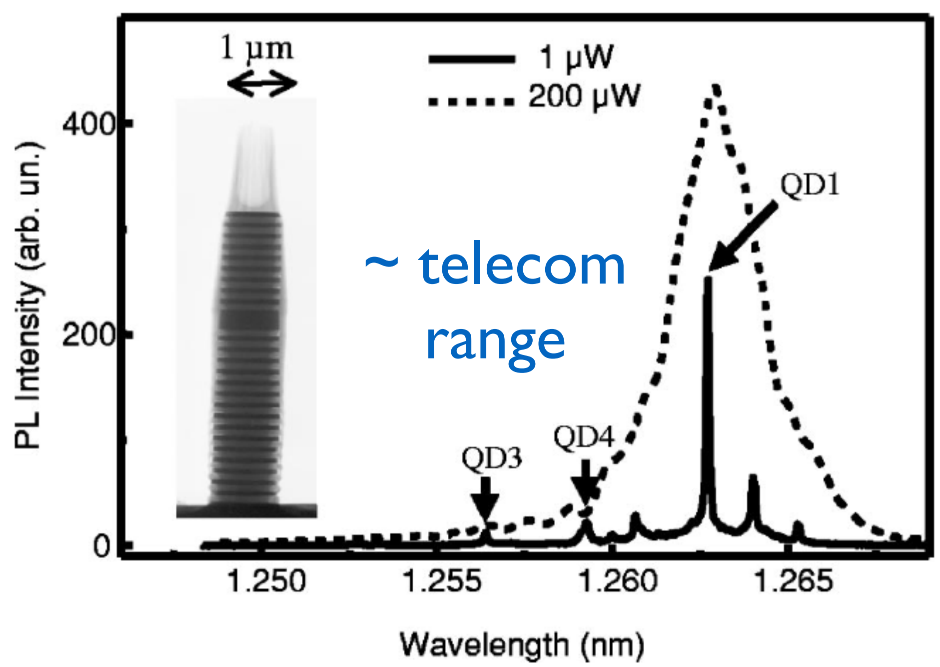

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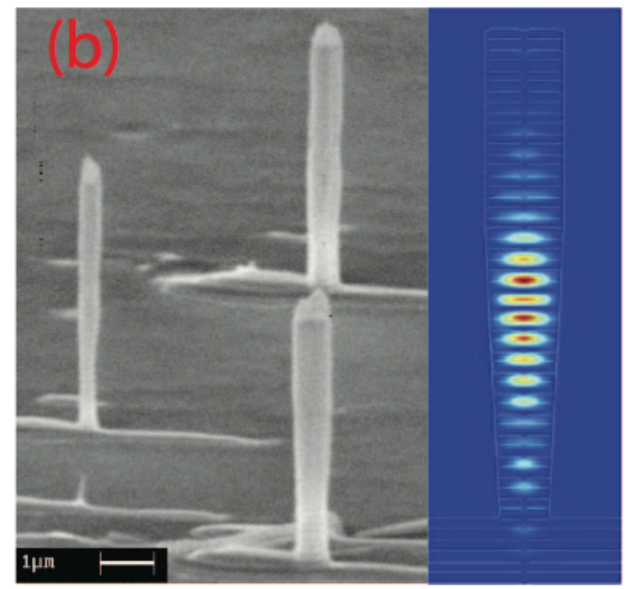
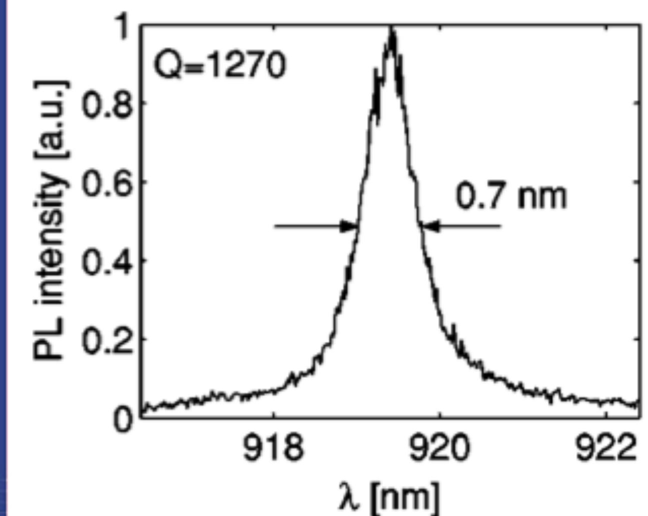
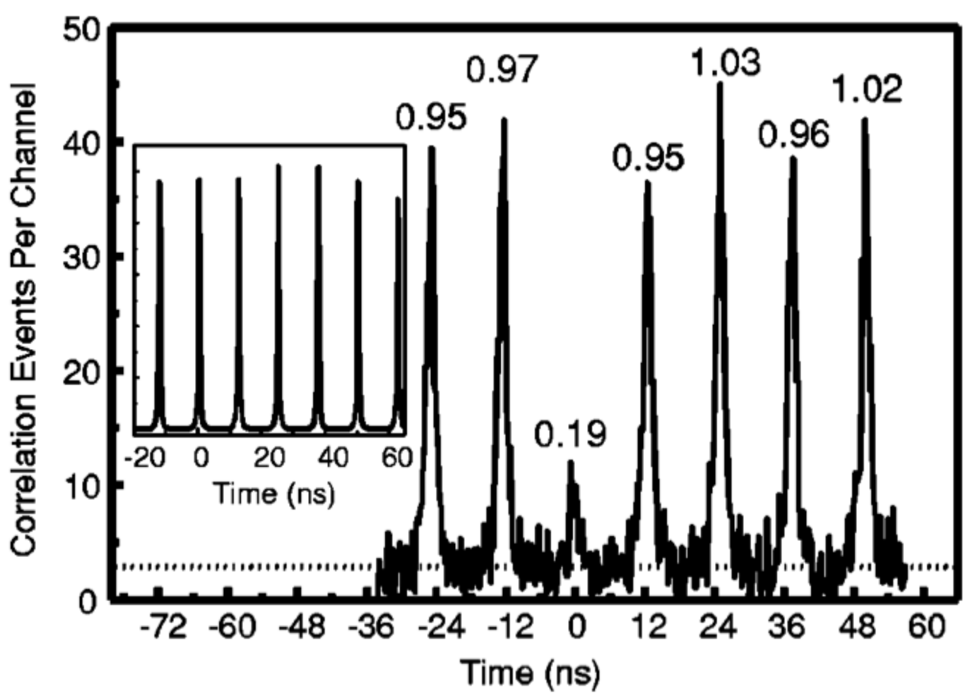
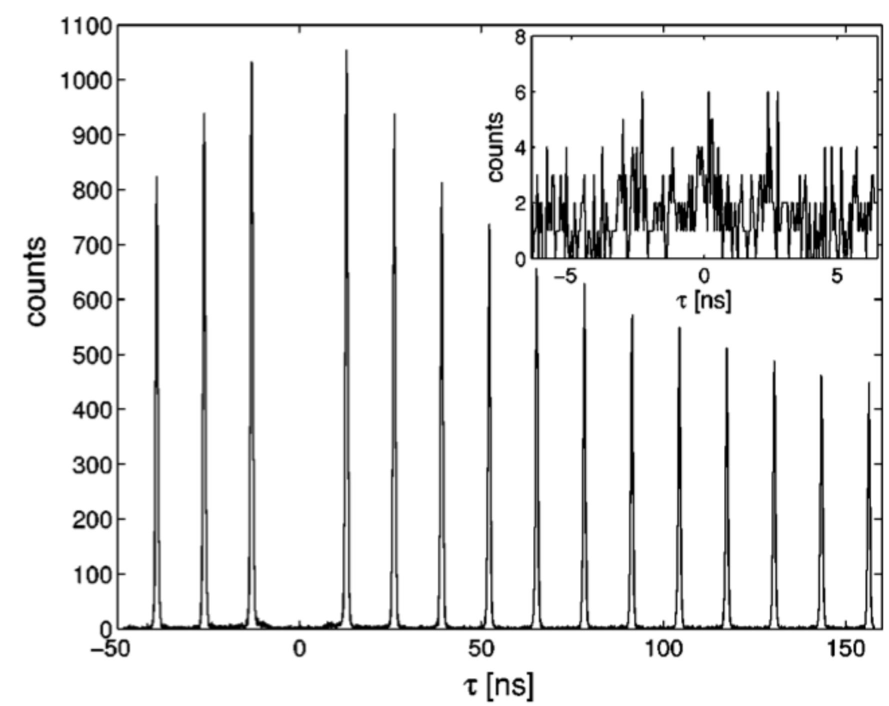




$g^{(2)}(0) \sim 0.19$, $Q \sim 400$, $\eta coll \sim 10^{-3}$



$g^{(2)}(0) \sim 0.02$, $Q \sim 4000$, $\eta coll \sim 10^{-2}$



2.3 Heralded SPS based on nonlinear optics

- **Spontaneous parametric downconversion (SPDC) in nonlinear optics**

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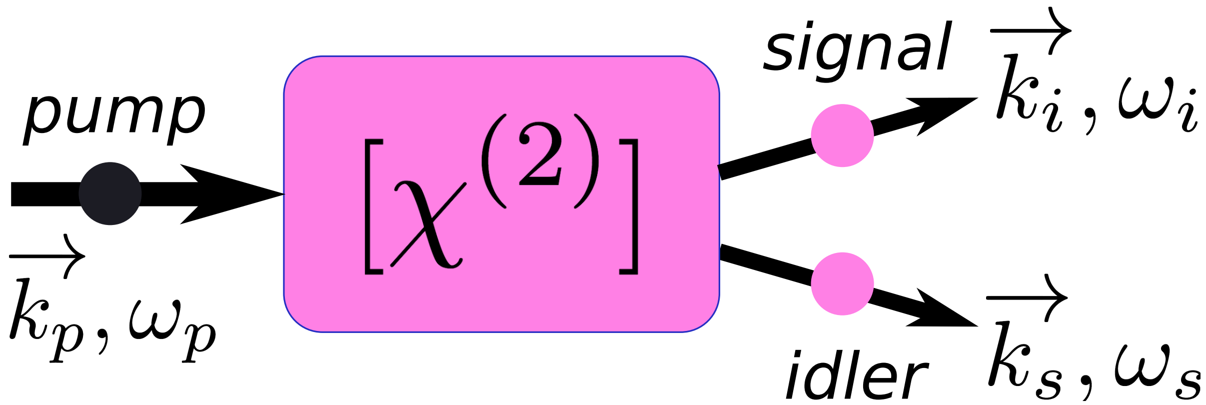

$\omega_p = \omega_s + \omega_i$ energy

$\vec{k}_p = \vec{k}_s + \vec{k}_i$ phase matching

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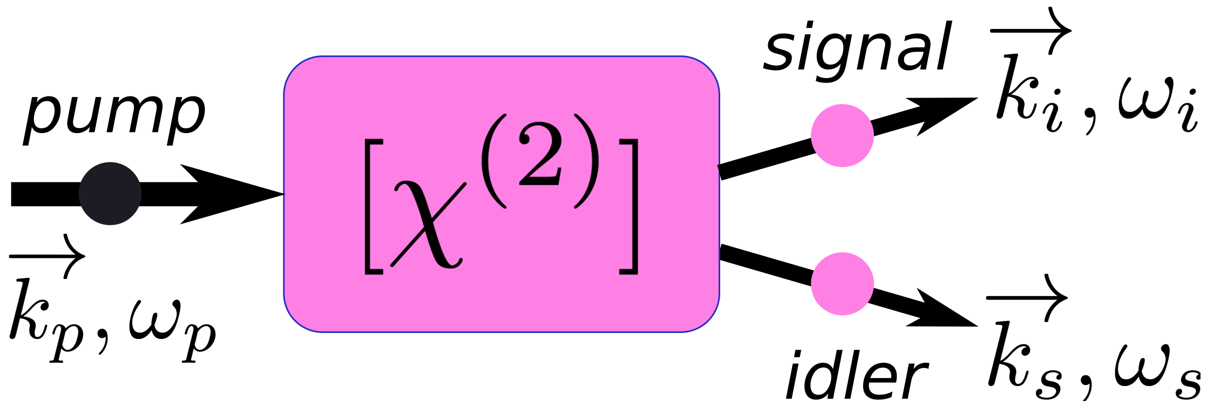

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Photon-pair emission ➜ Poissonnian distribution (pump laser)

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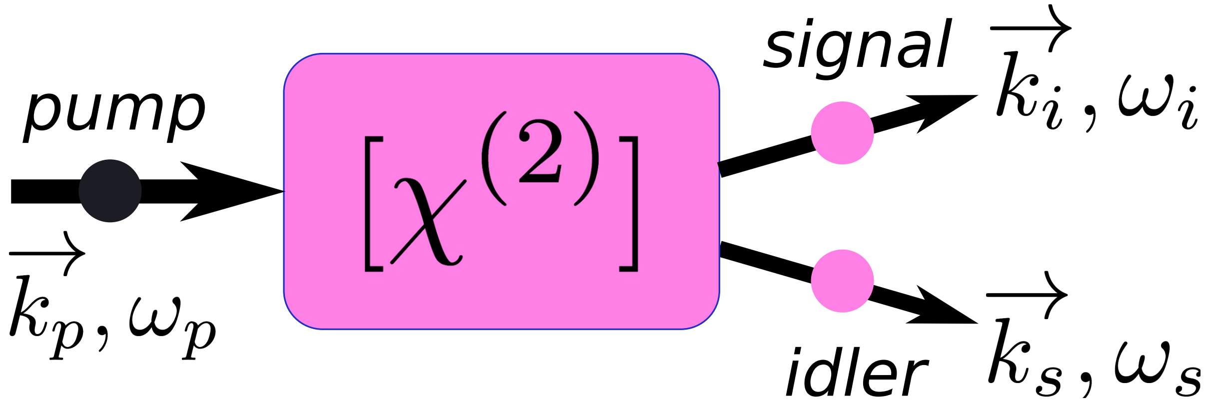

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- Emission of non degenerate paired photons by SPDC emitted simultaneously
- Detection of the signal photon (shorter λs) for heralding the idler photon (λi)

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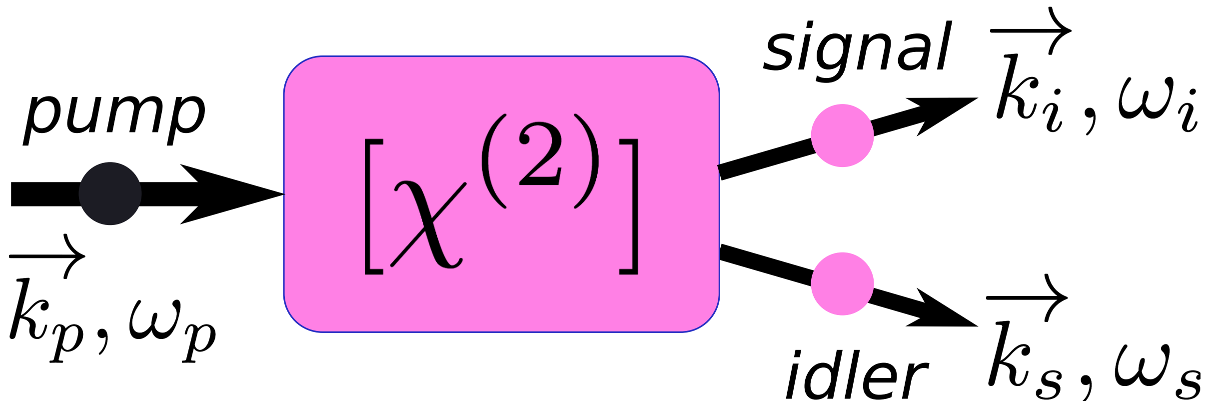

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- **Single photon emission character ?**

  - Emission of non degenerate paired photons by SPDC emitted simultaneously
  - Detection of the signal photon (shorter λs) for heralding the idler photon (λi)

➜ Reduces both empty pulses and detection noise
➜ Reduces the emission statistics to **sub-Poissonnian distributions (antibunching)**
➜ Emission regime is asynchronous !
➜ Prevents from observing standard antibunching curves !

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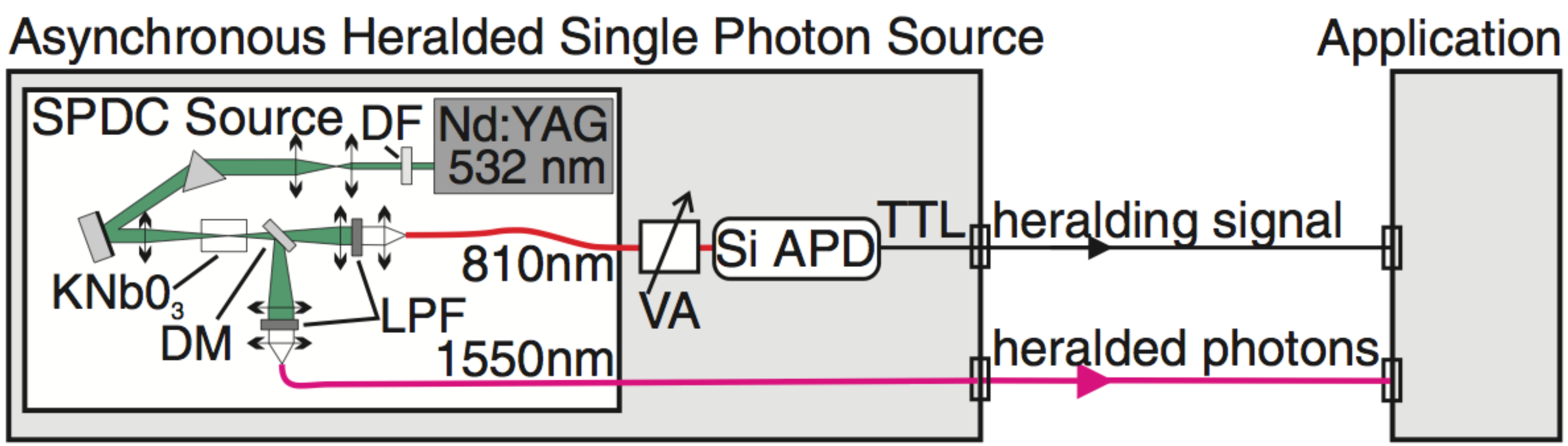
- **Standard setup based on a bulk crystal**



[Gisin's group, Geneva] S. Fasel *et al.*, NJP **6**, 163 (2004)

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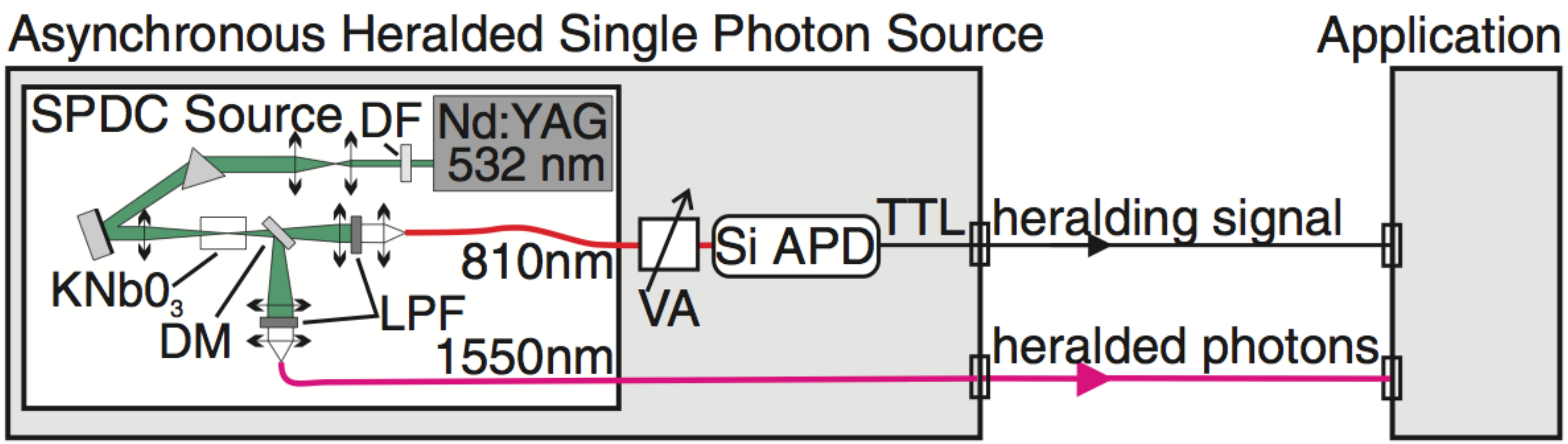

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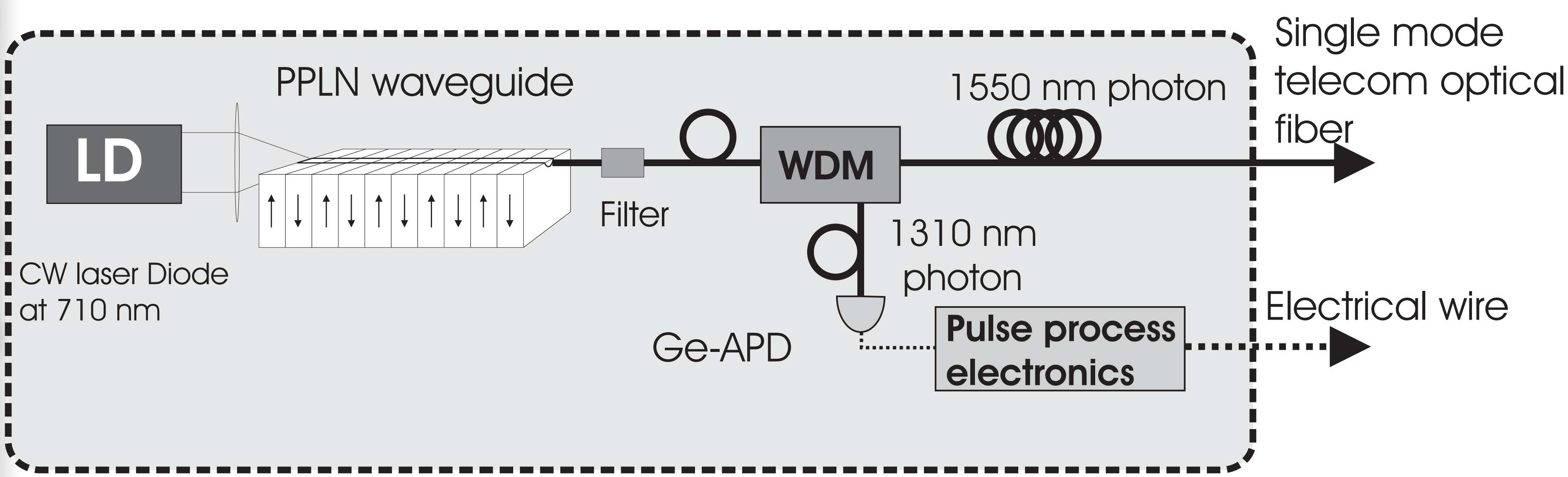

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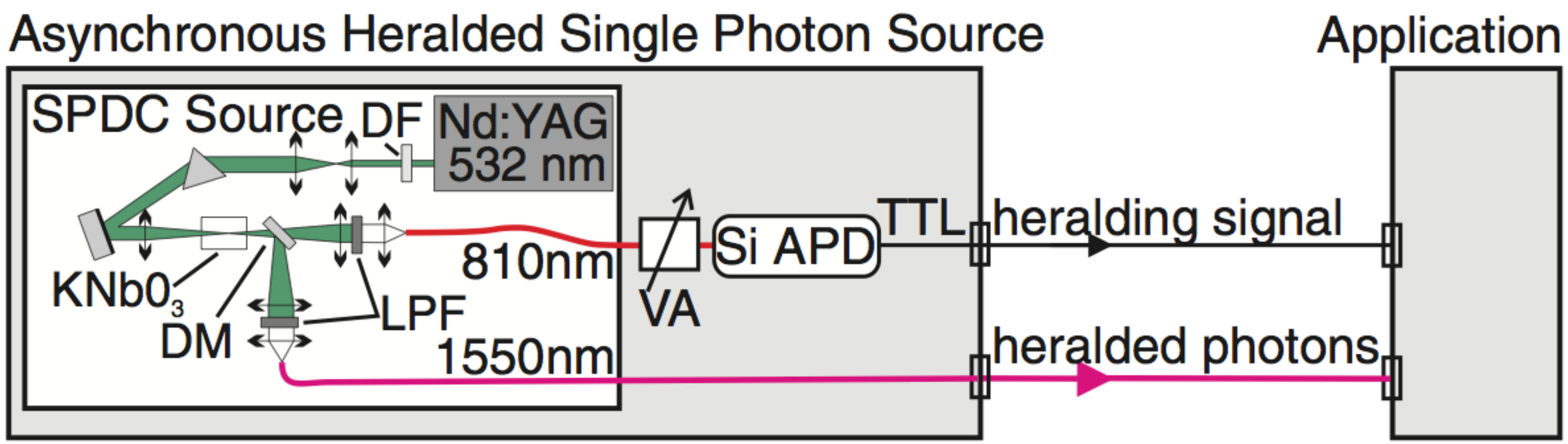

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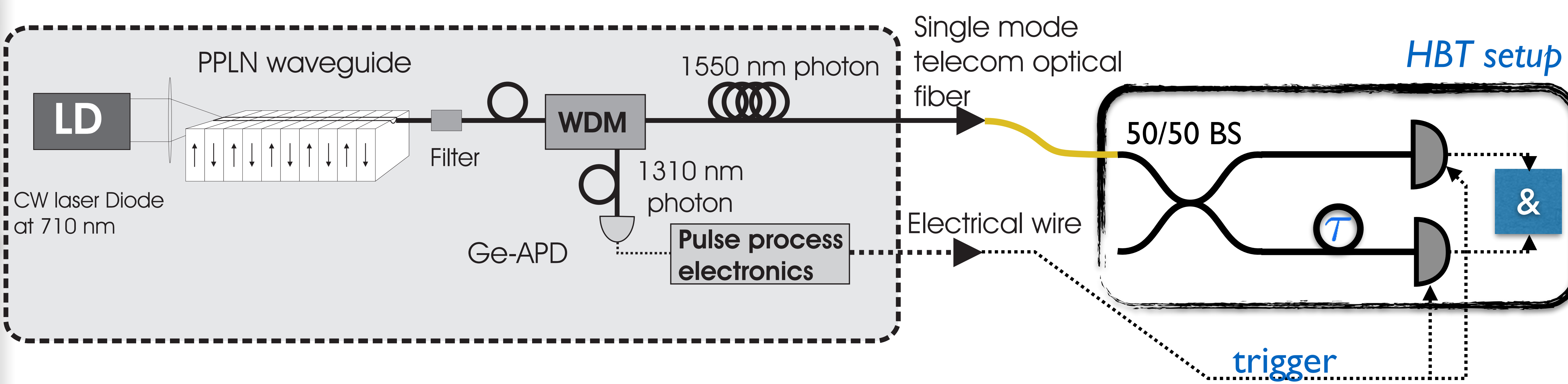

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Autocorr. function

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Autocorr. function $$g^{(2)}(0) = \frac{2P_2}{P_1^2}$$

Assuming a Poissonnian distrib.

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Assuming a Poissonnian distrib.

Typical experimental parameters: $\eta_{coll} \sim 0.5$, $\Delta T \sim 1$ ns, $\mu \sim 10^6$ pairs/s

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Antibunching measurements ➜ a much clever approach

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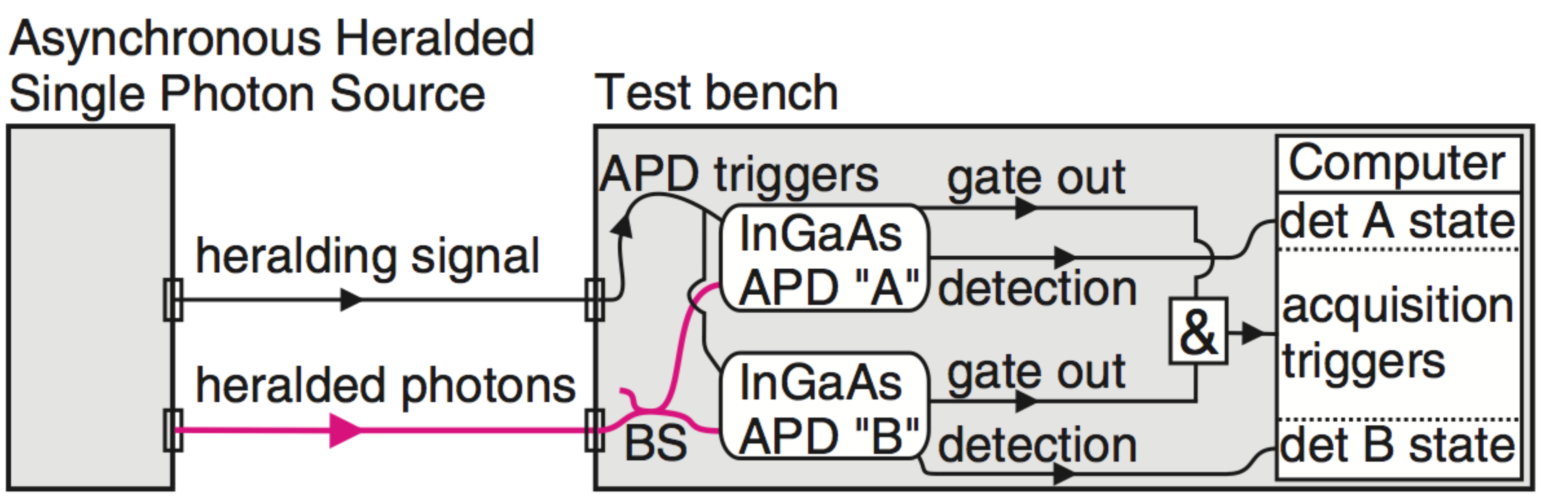

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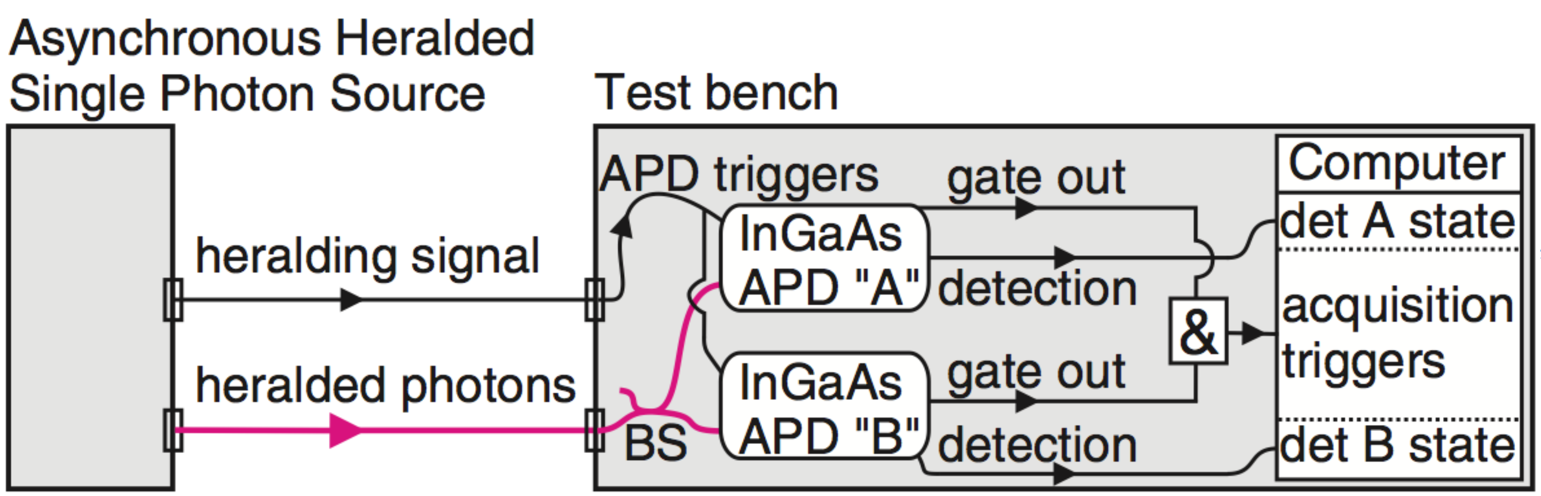

	det A	det B	
	...	...	
no detection	0	0	$n = -1$
start at A	1	0	$n = 0$
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invalid start	1	0	$n = +2$
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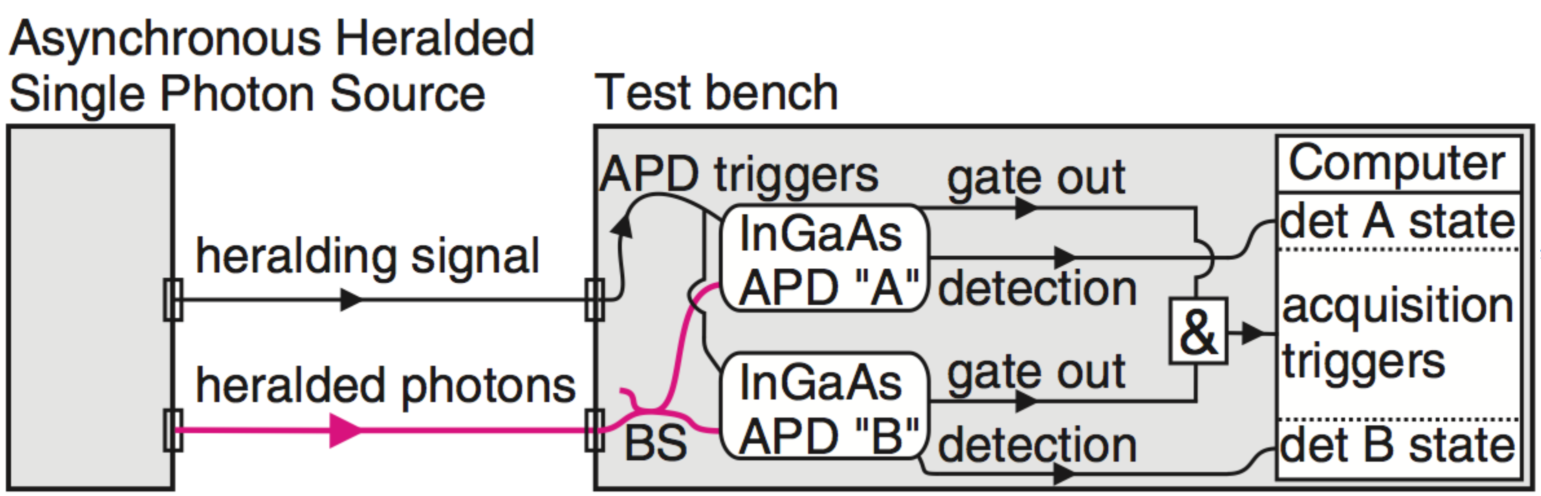

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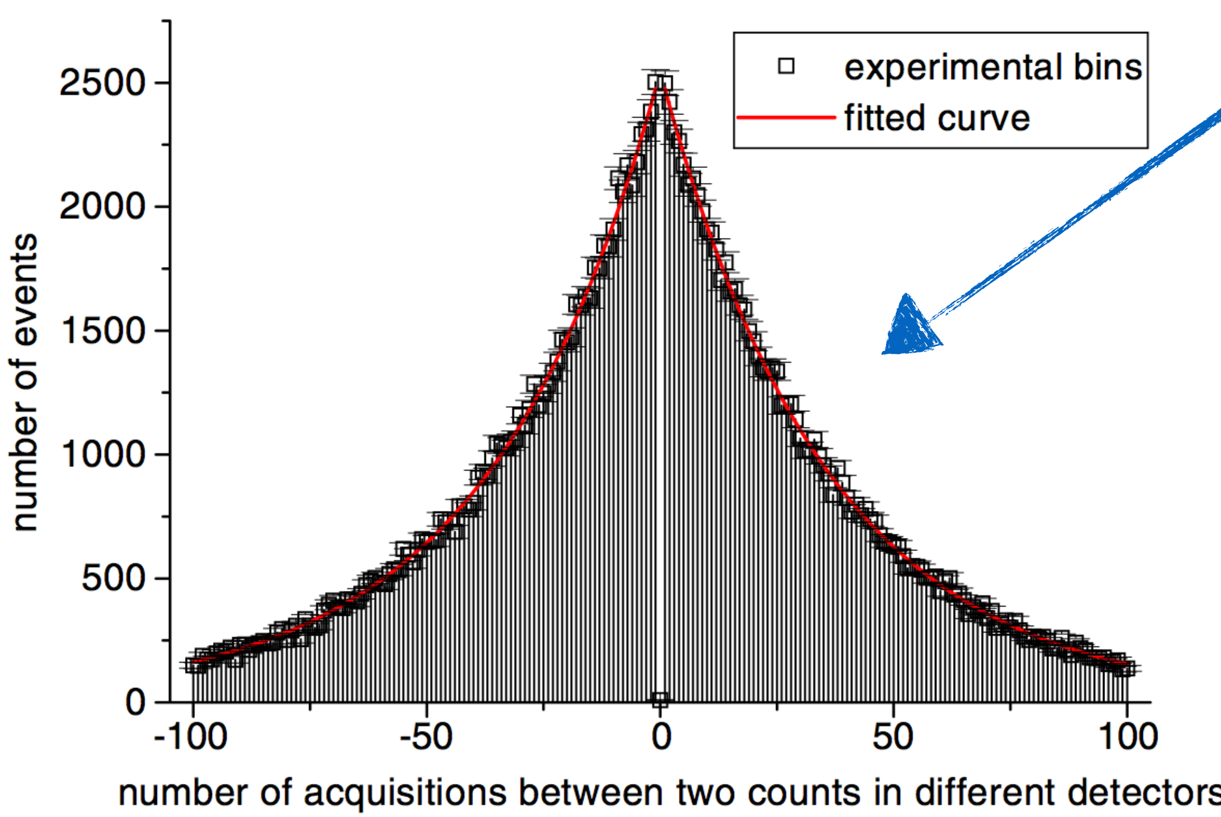
- **Results**



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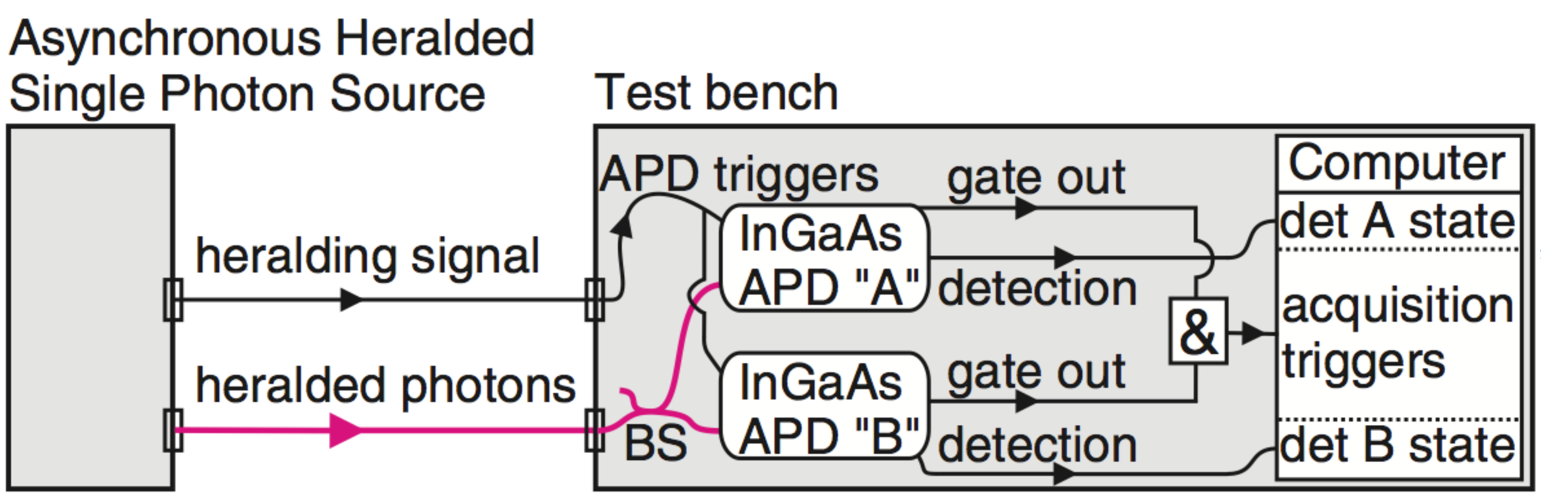

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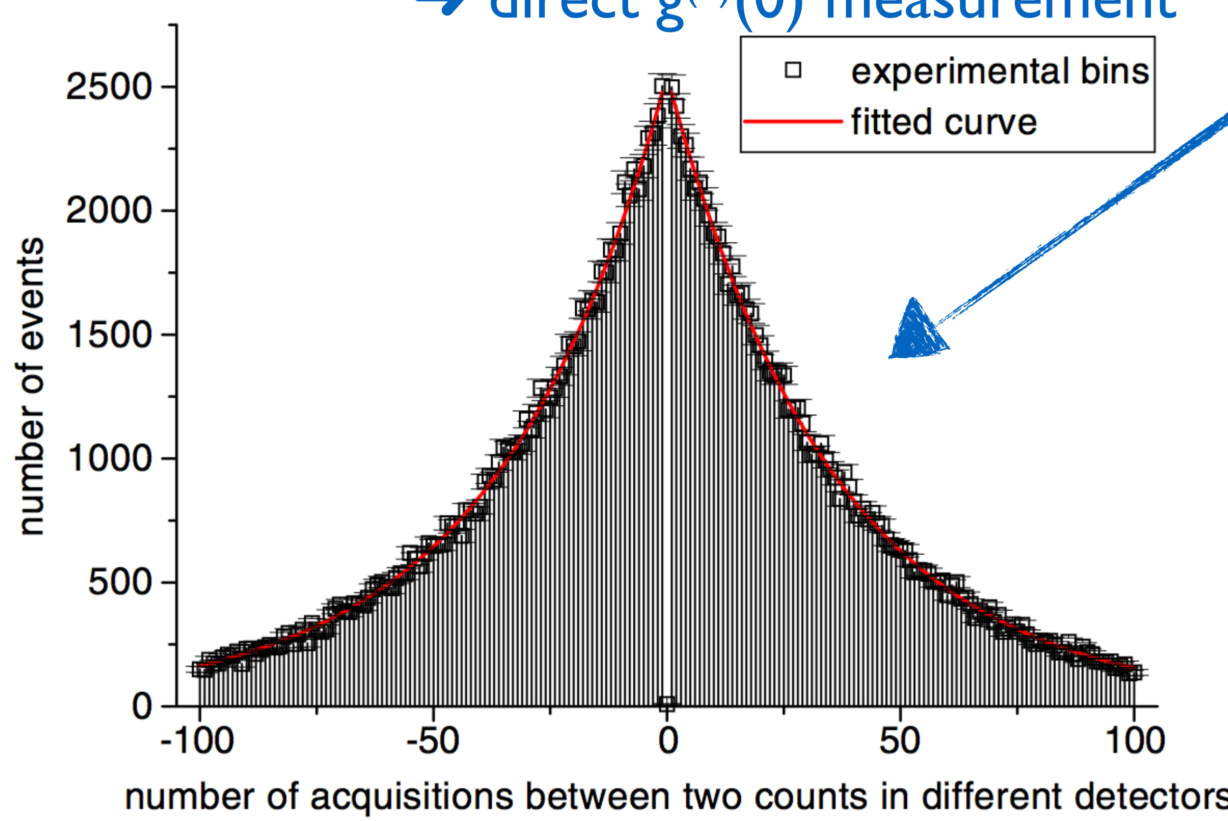
- **Results** Same as obtained with "true" SPS
  ➜ direct $g^{(2)}(0)$ measurement



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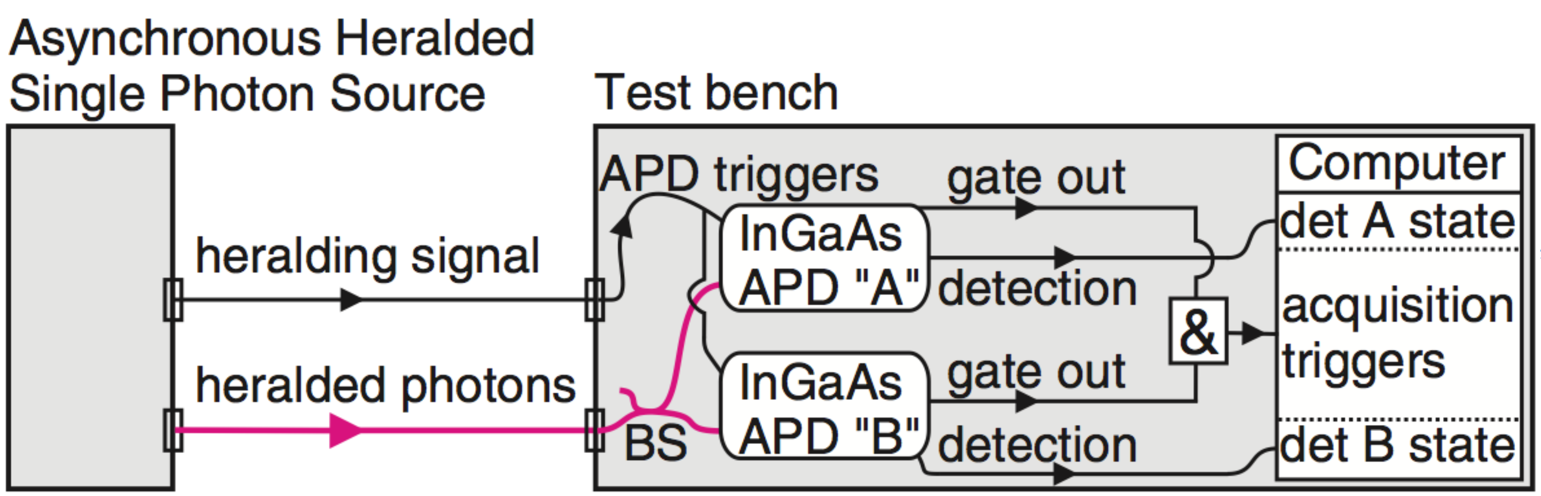

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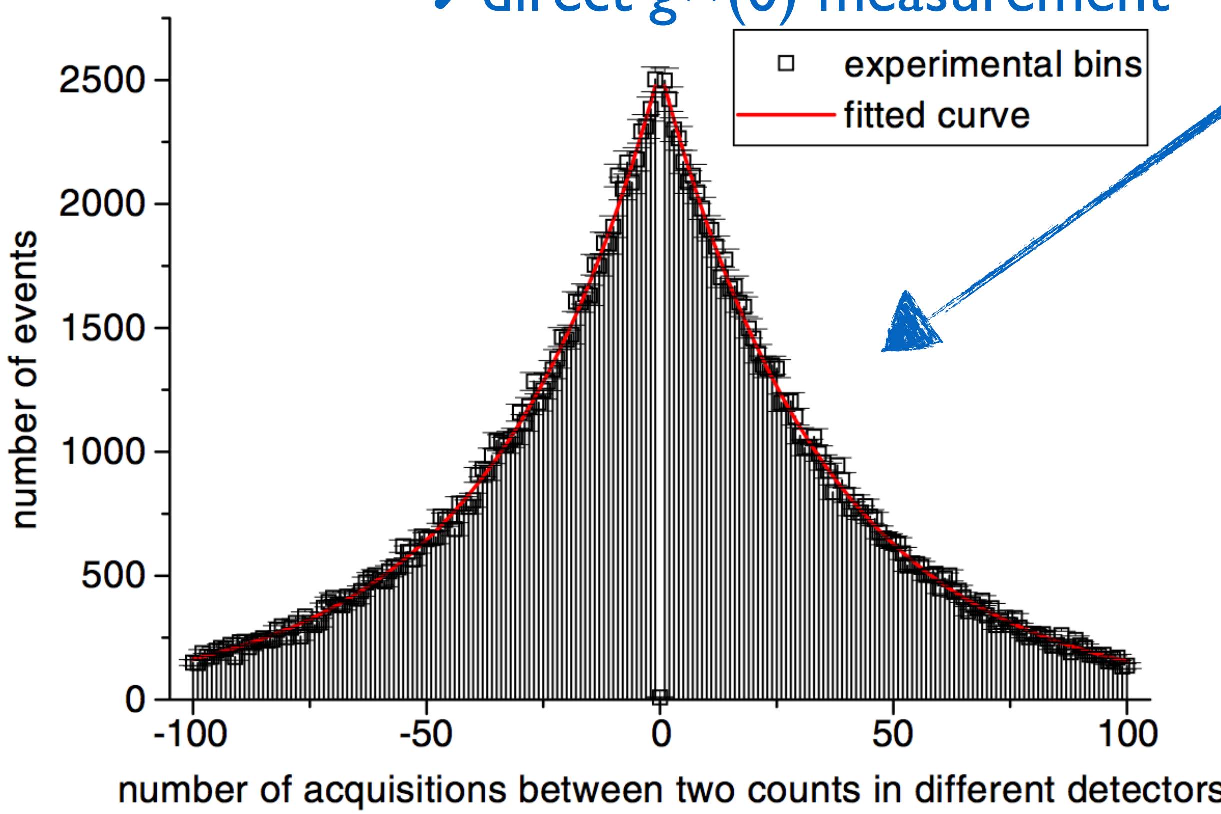

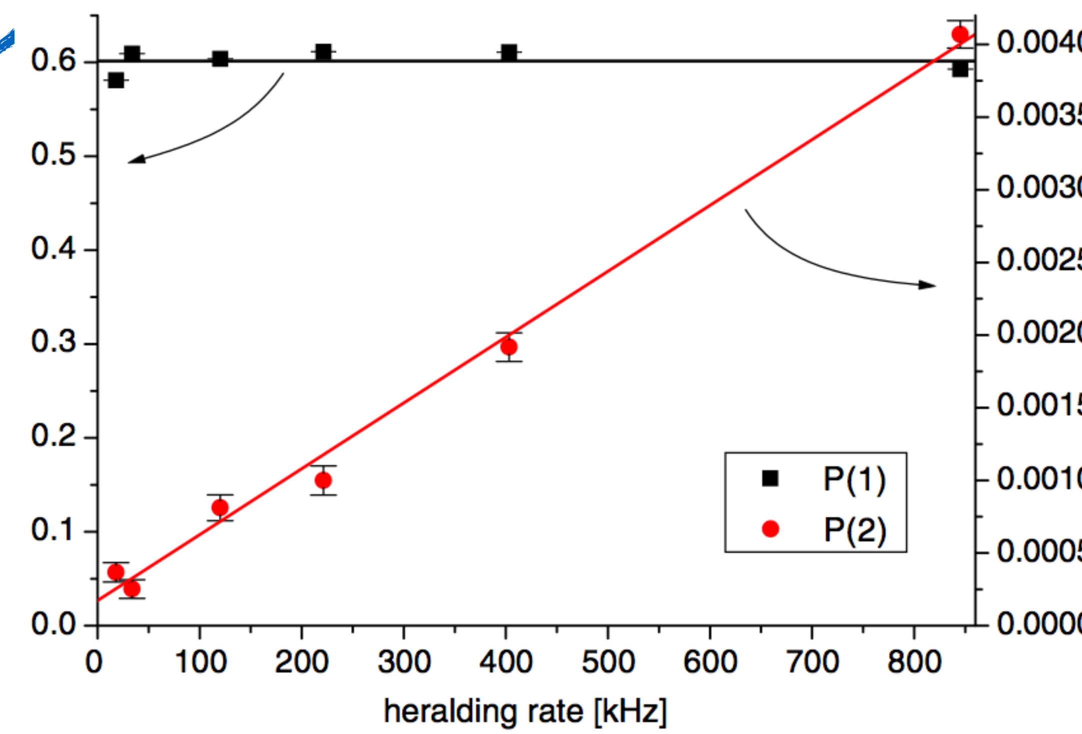

Laboratoire Physique de la Matière Condensée

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Summary and future directions

- Summary

Source	λ (nm)	P0	P1	P2	g
Waveguide	1550 / 1310	0.63	0.37	7.10	0.08
Bulk	1550 / 810	0.39	0.61	2.10	2.10

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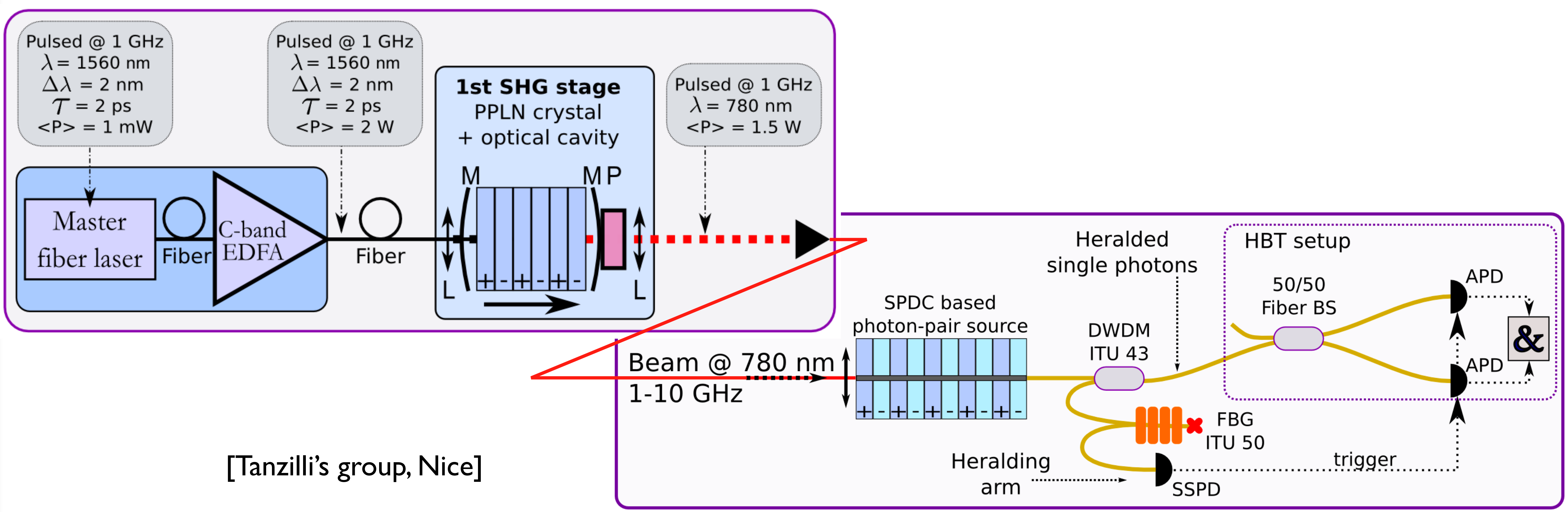
- **Towards Ultrafast heralding rates ➜ 10 MHz**



[Tanzilli's group, Nice]

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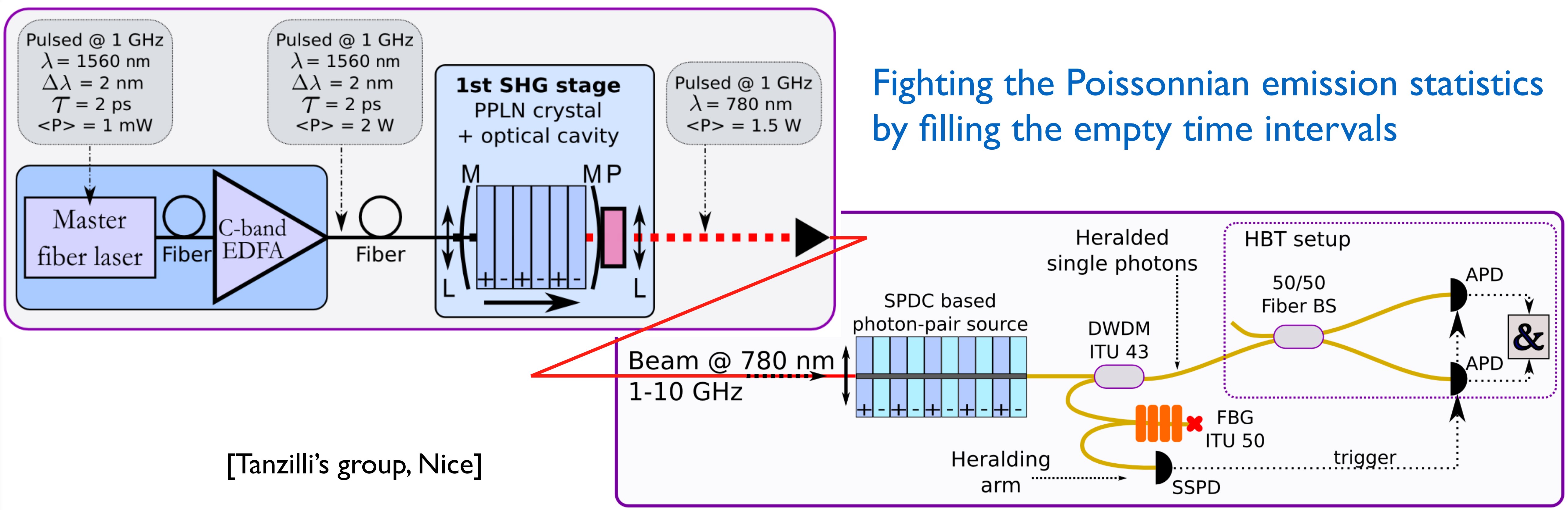
Source	λ (nm)	P0	P1	P2	g
Waveguide	1550 / 1310	0.63	0.37	7.10	0.08
Bulk	1550 / 810	0.39	0.61	2.10	2.10

- **Towards Ultrafast heralding rates ➜ 10 MHz**

Fighting the Poissonnian emission statistics by filling the empty time intervals

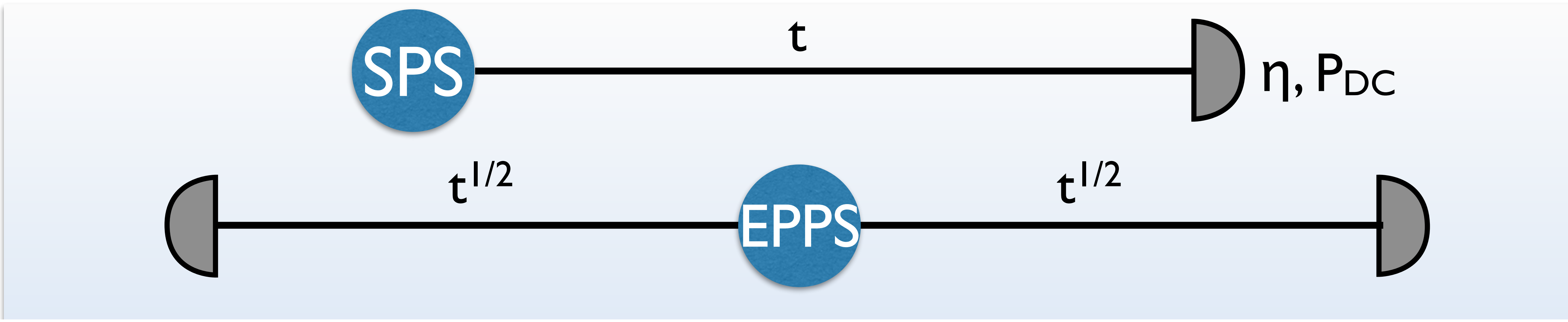


[Tanzilli's group, Nice]

2.4 Connecting HSPs for quantum networks

- **The context of today's quantum communication**

  Distribution of quantum bits of information
  using single photon and entangled photon pair sources



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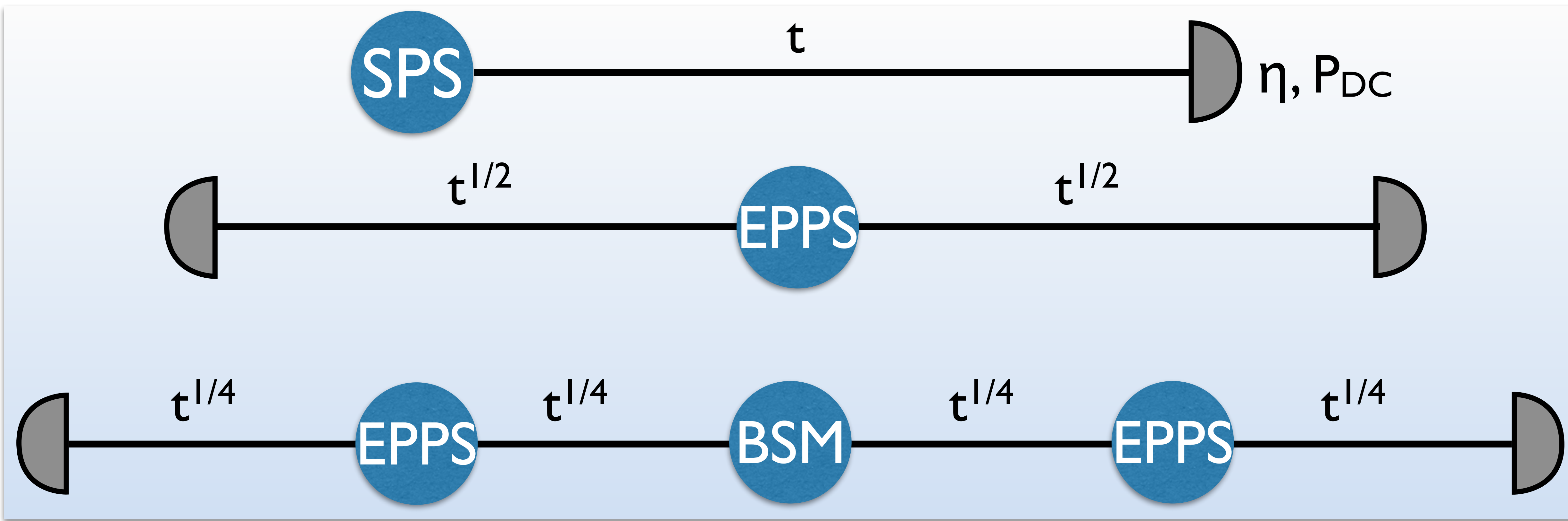

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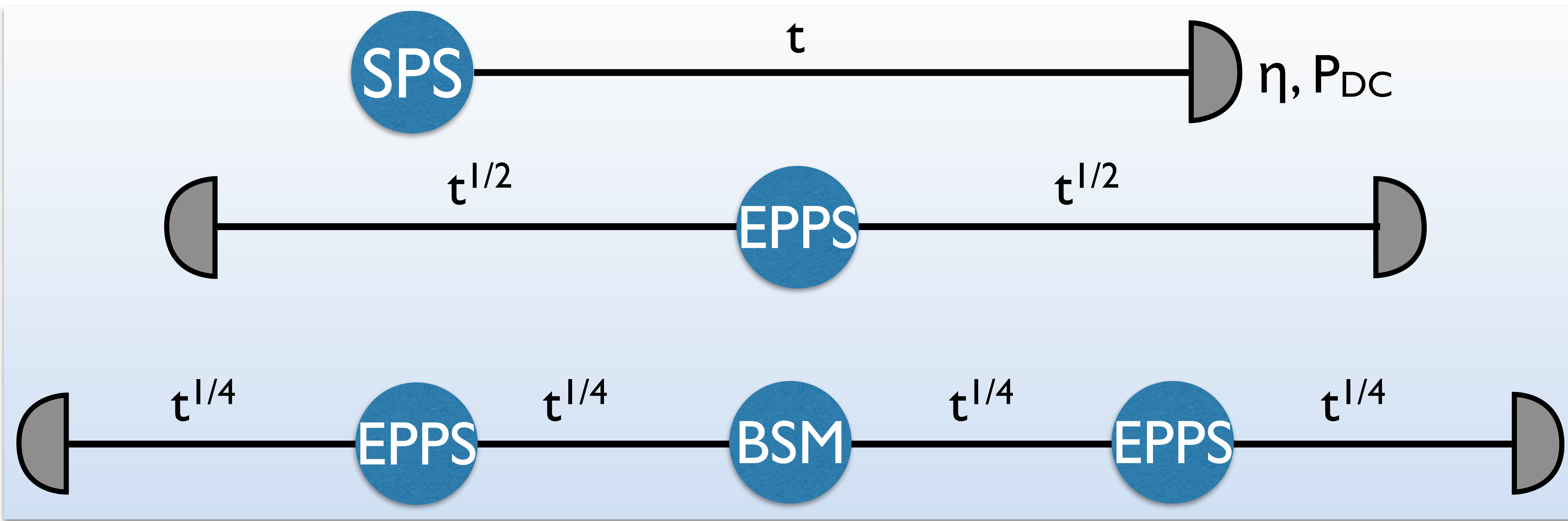

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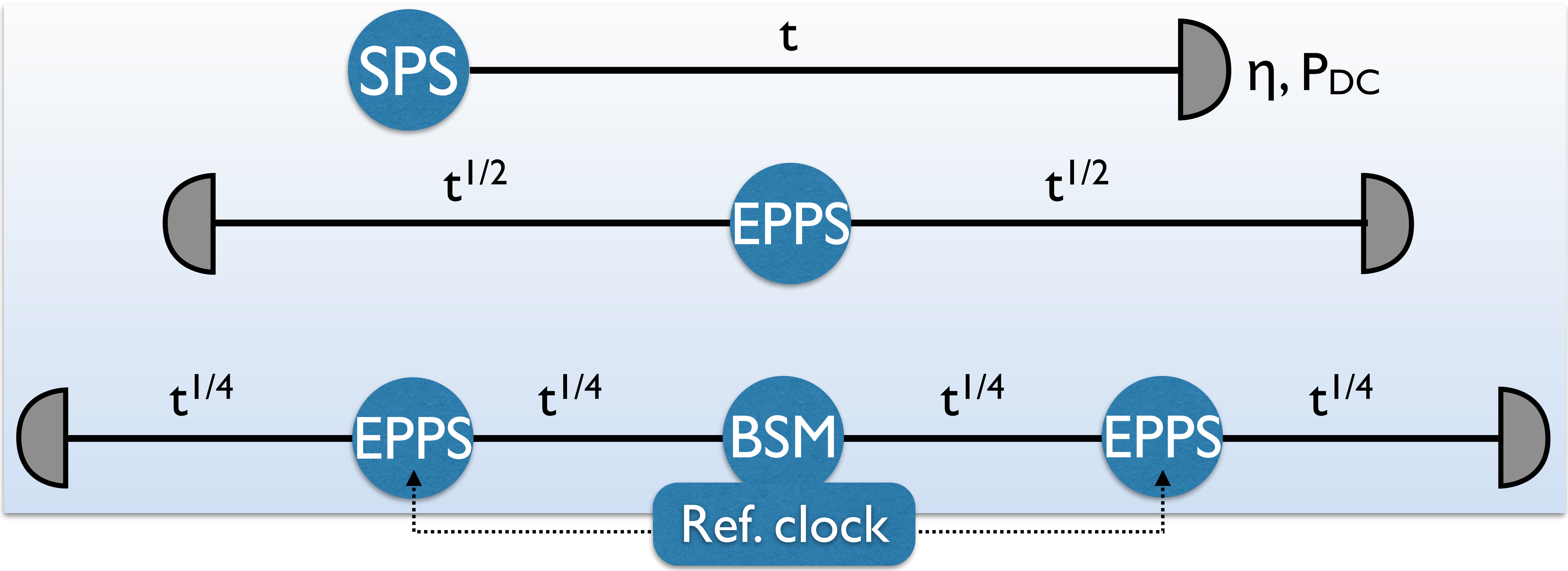

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  ➜ Needs a synchronization procedure, and identical photons (!)

2.4 Connecting HSPs: how does the HOM effect work ?

One photon in spatial mode a ➜

C. K. Hong *et al.*, PRL **59**, 2044 (1987)

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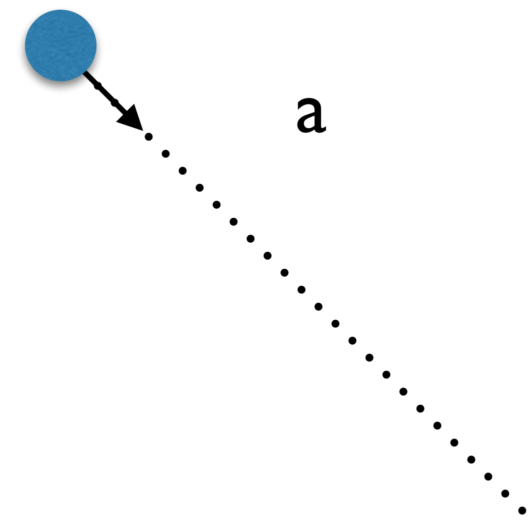

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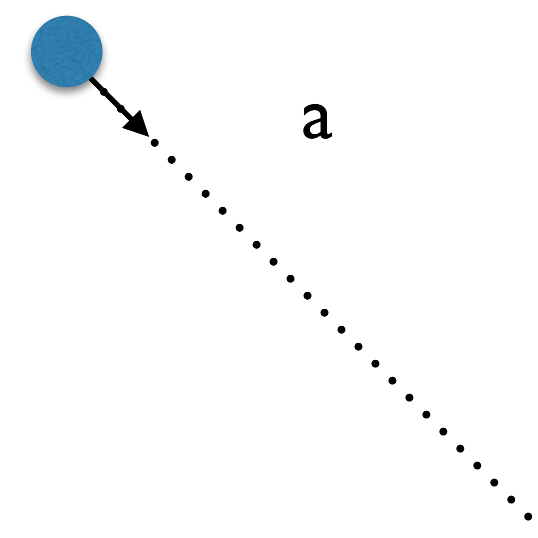

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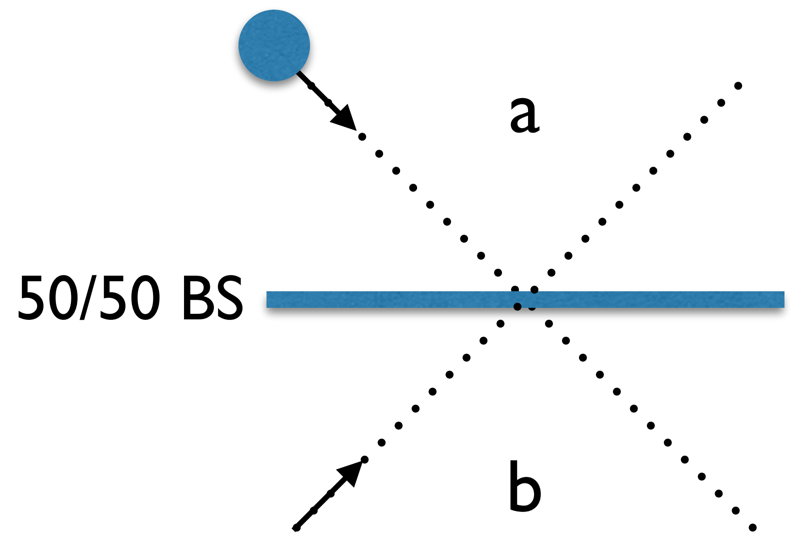

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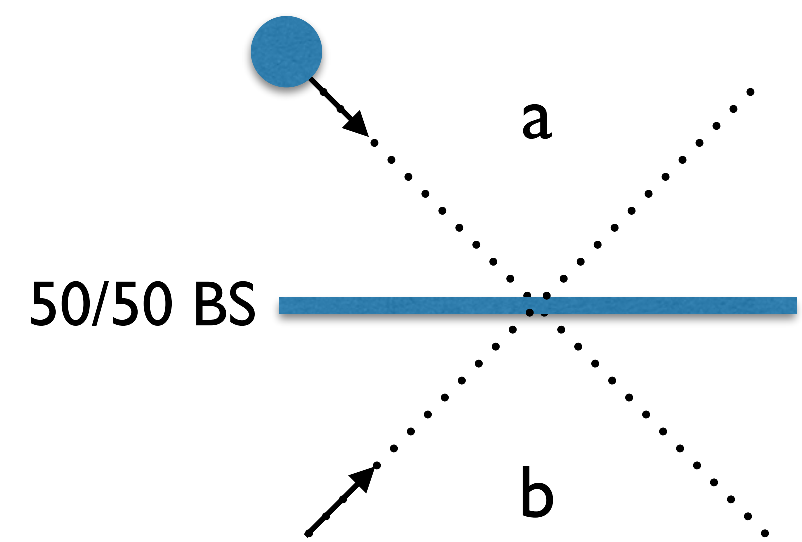

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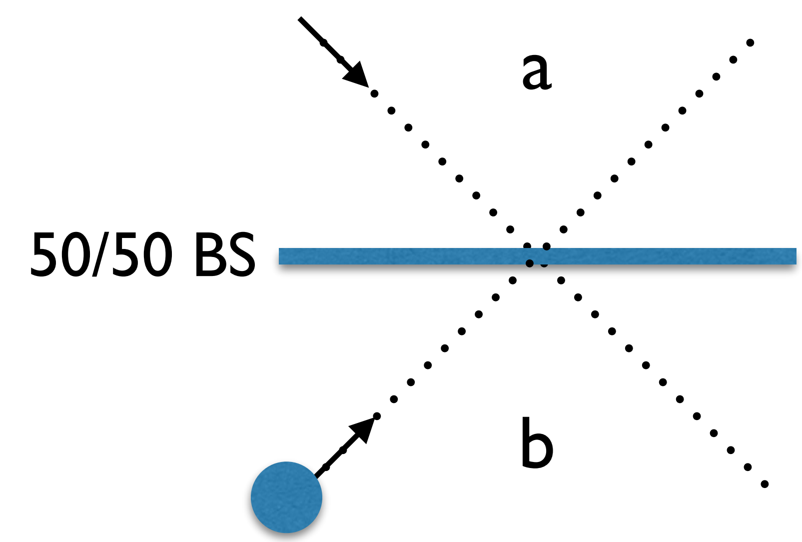

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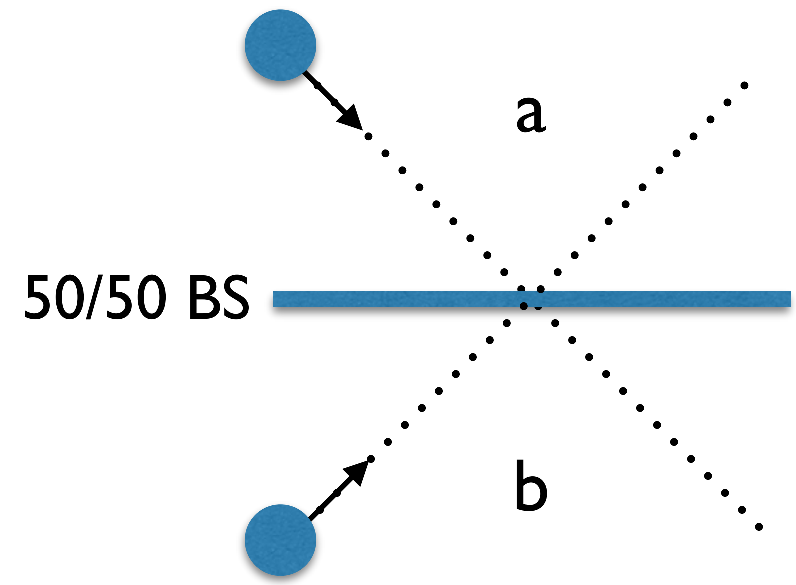

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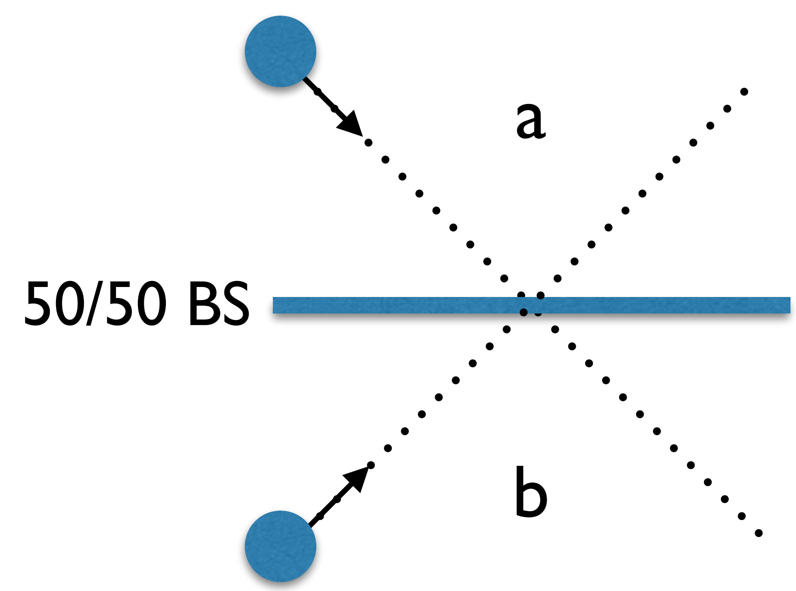

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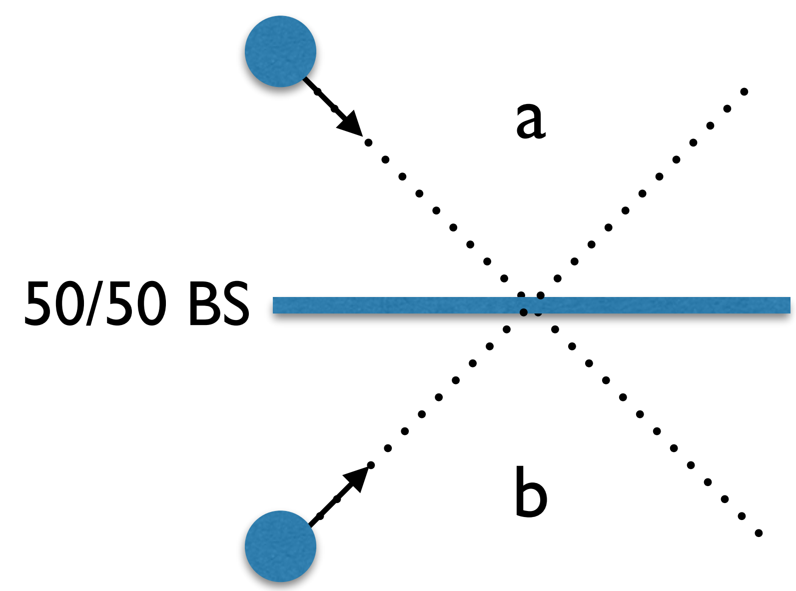

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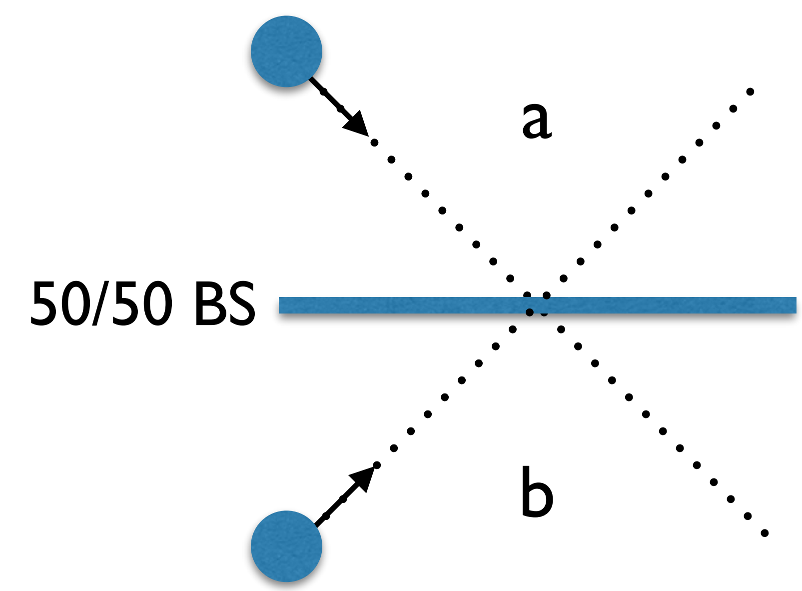

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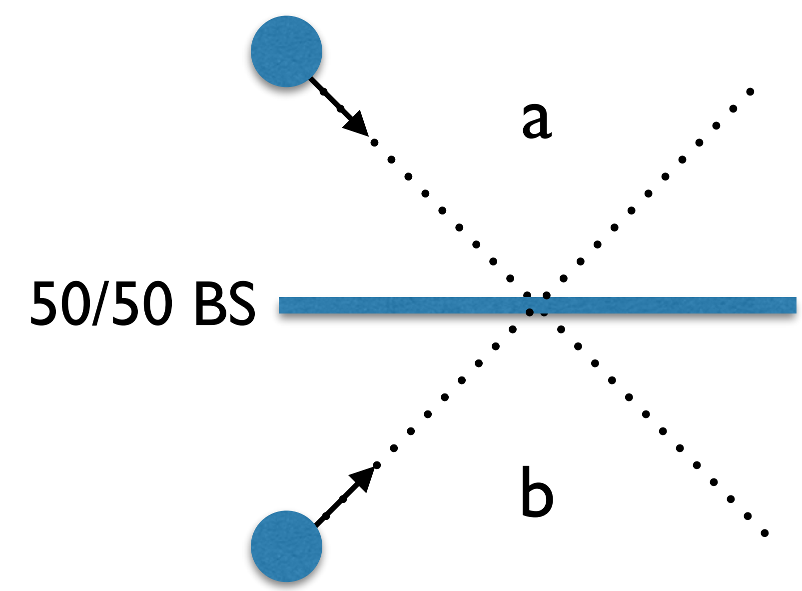

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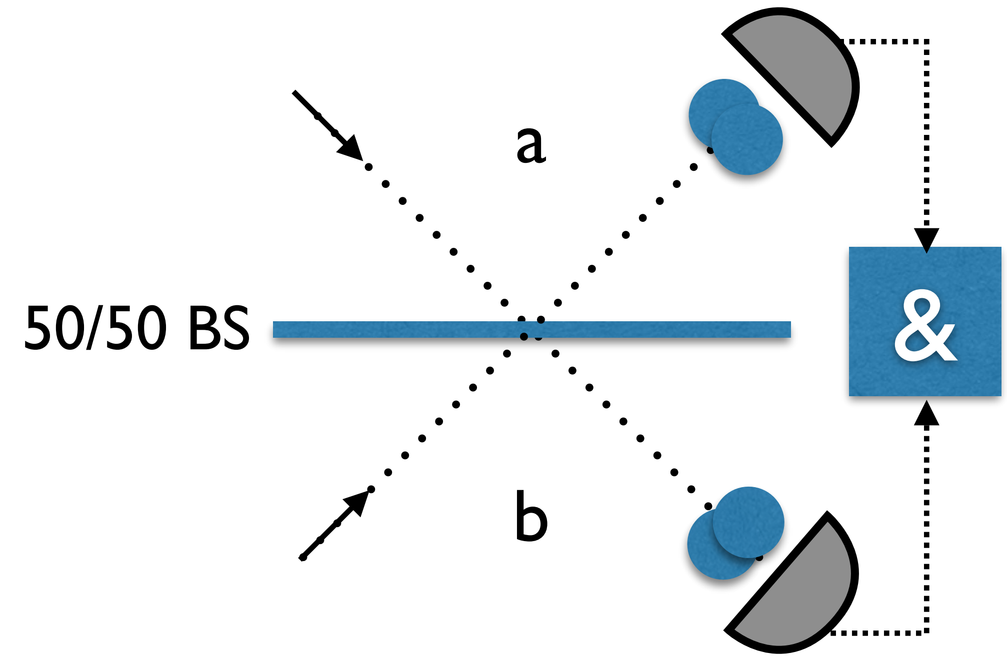

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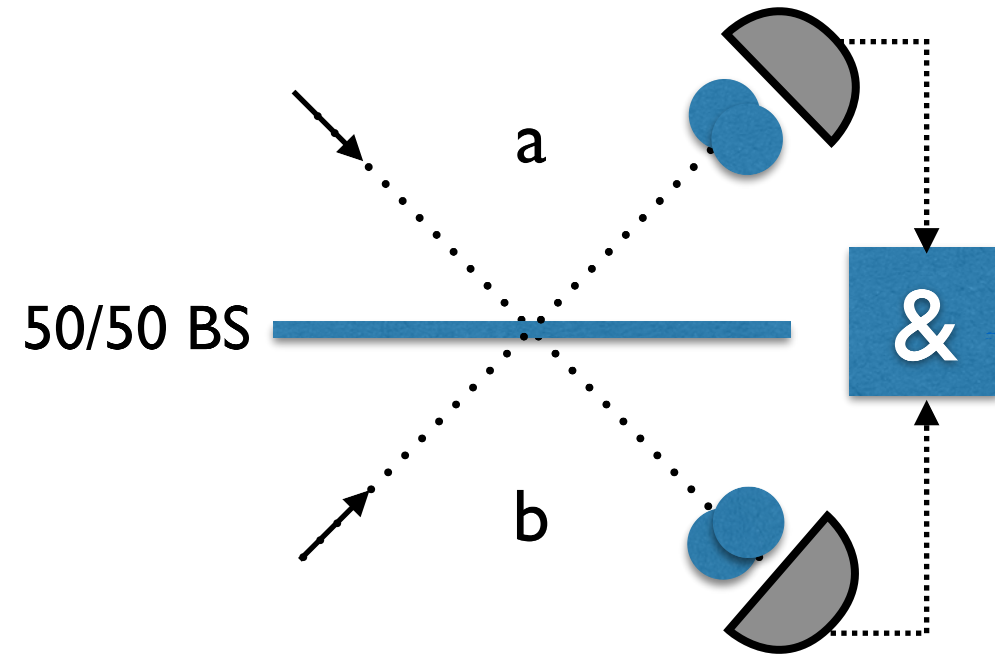

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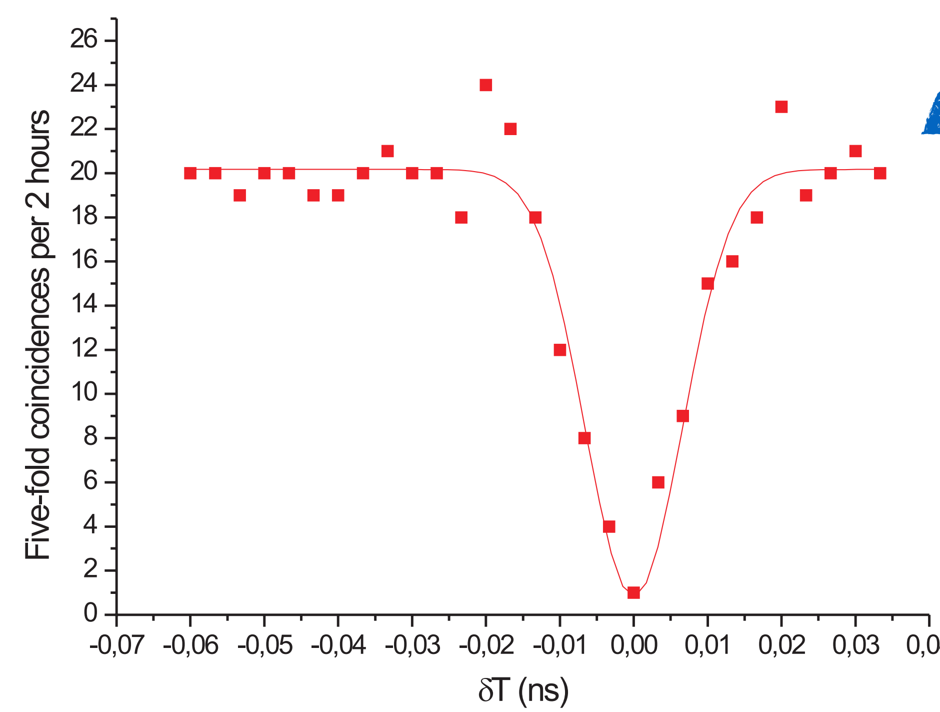
HOM effect: dip in the coincidence counts



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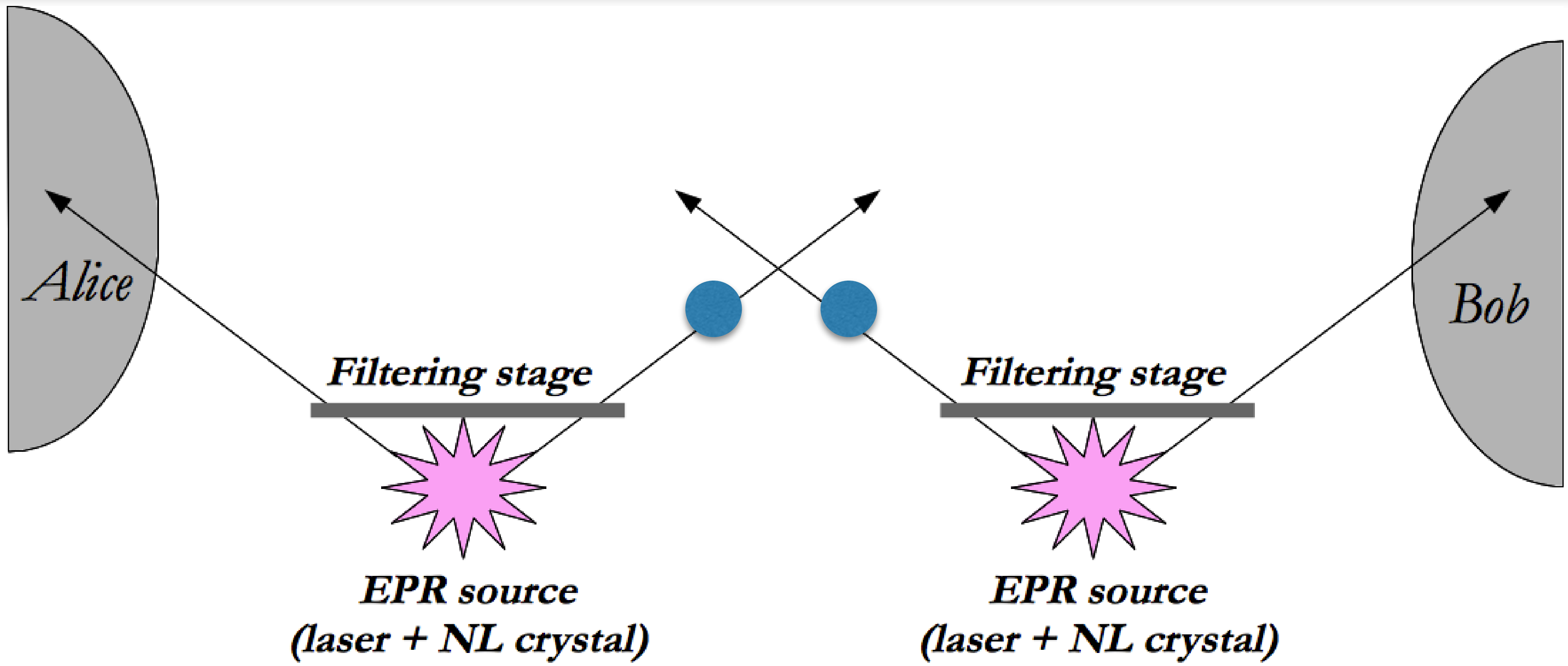

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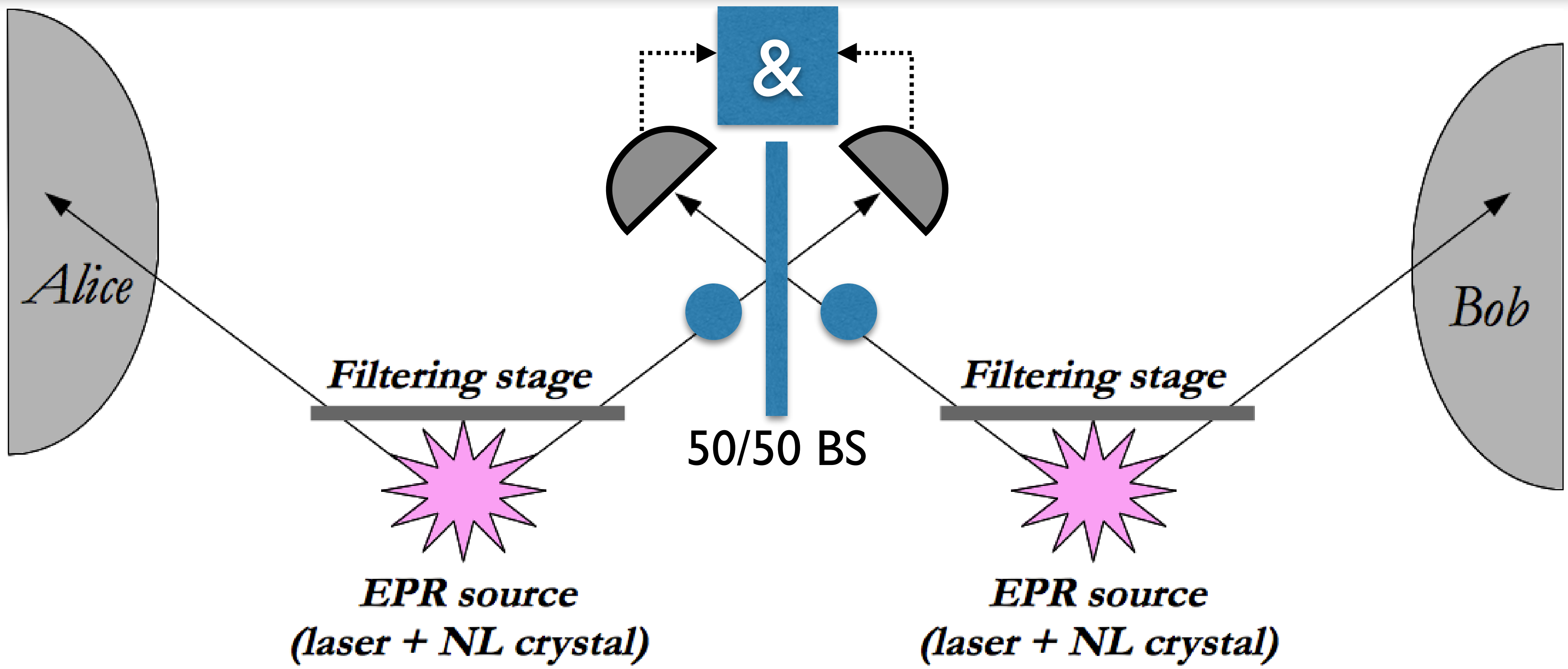

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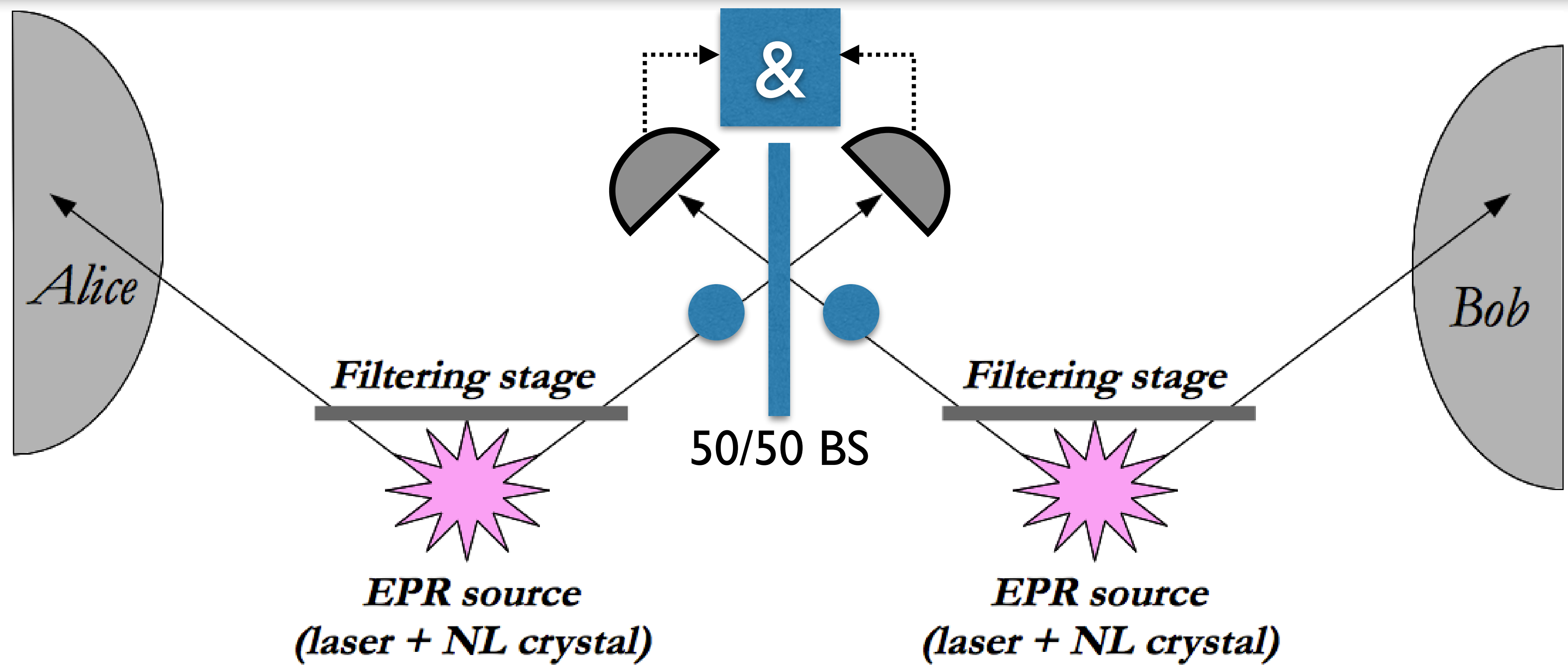

Indistinguishable photons should have identical

- Wavelengths (λ)
- Spectra (Δλ)
- Arrival times at the BS
- Polarization modes
- Spatial mode (maximal spatial overlap at the BS)

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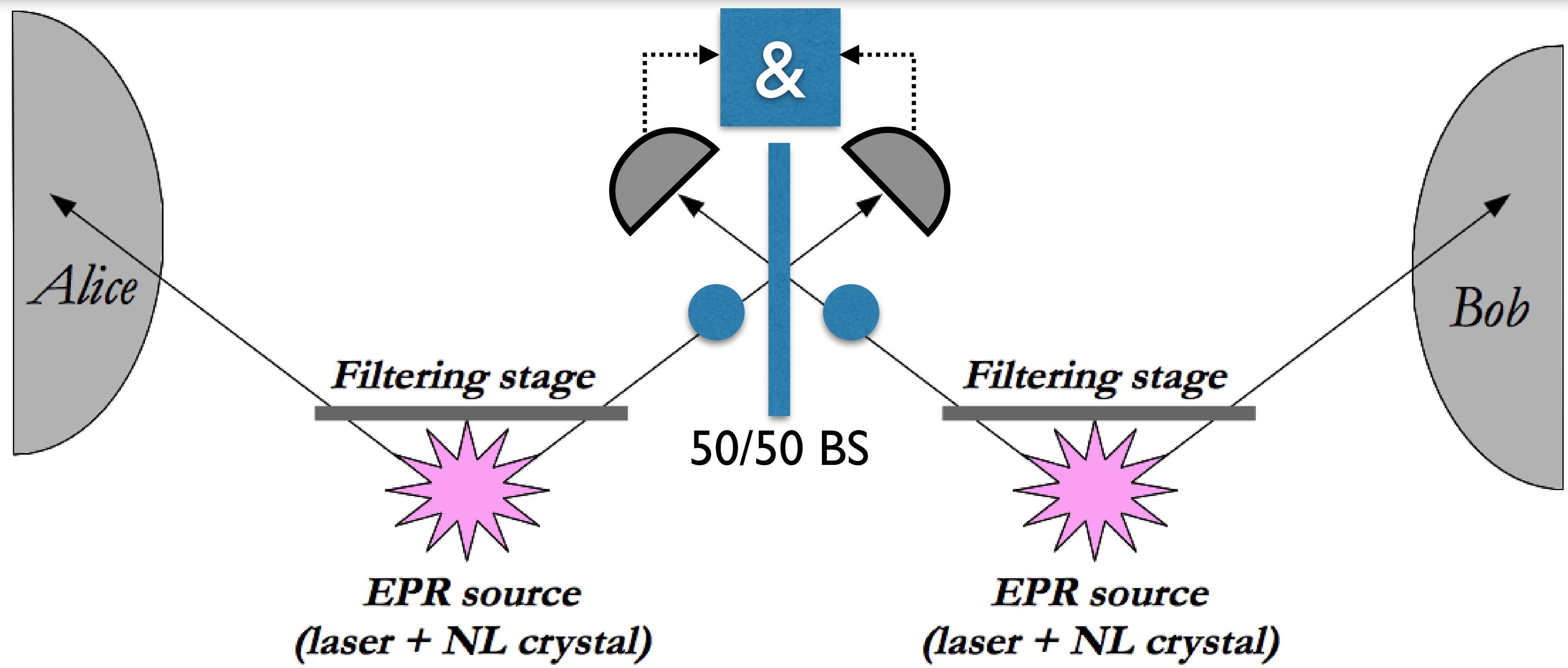

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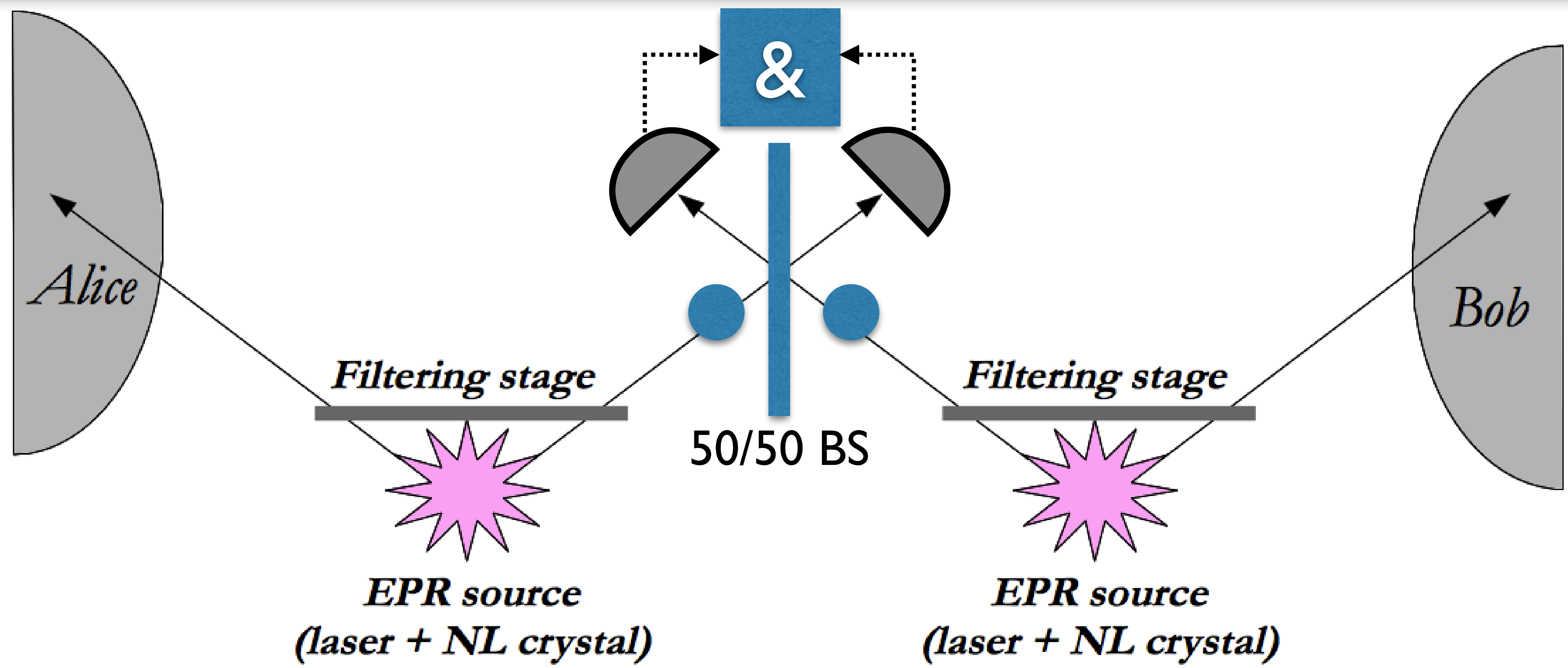

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- Both in a single temporal mode

Achieved by

- Phase matching in the Xtals
- Filtering stages
- Synchronization
- Polarization controllers
- Single mode fibers
- HBT measurement !

2.4 Connecting HSPs: single temporal mode

- **The photons are created in a multimode manner**

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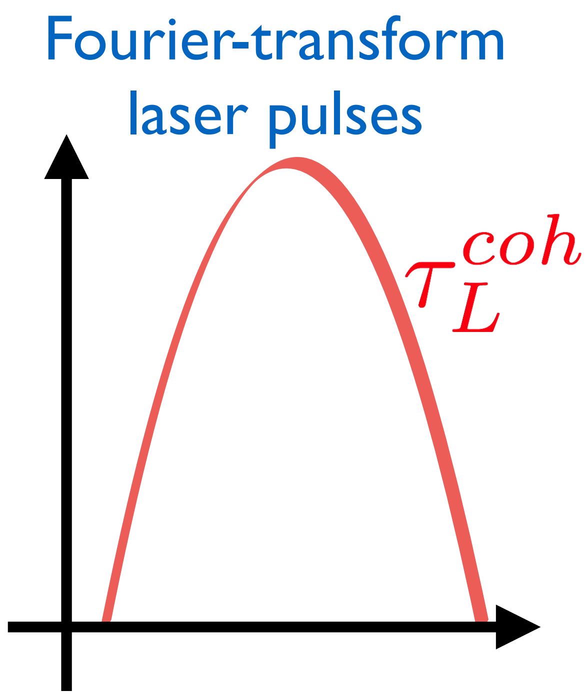

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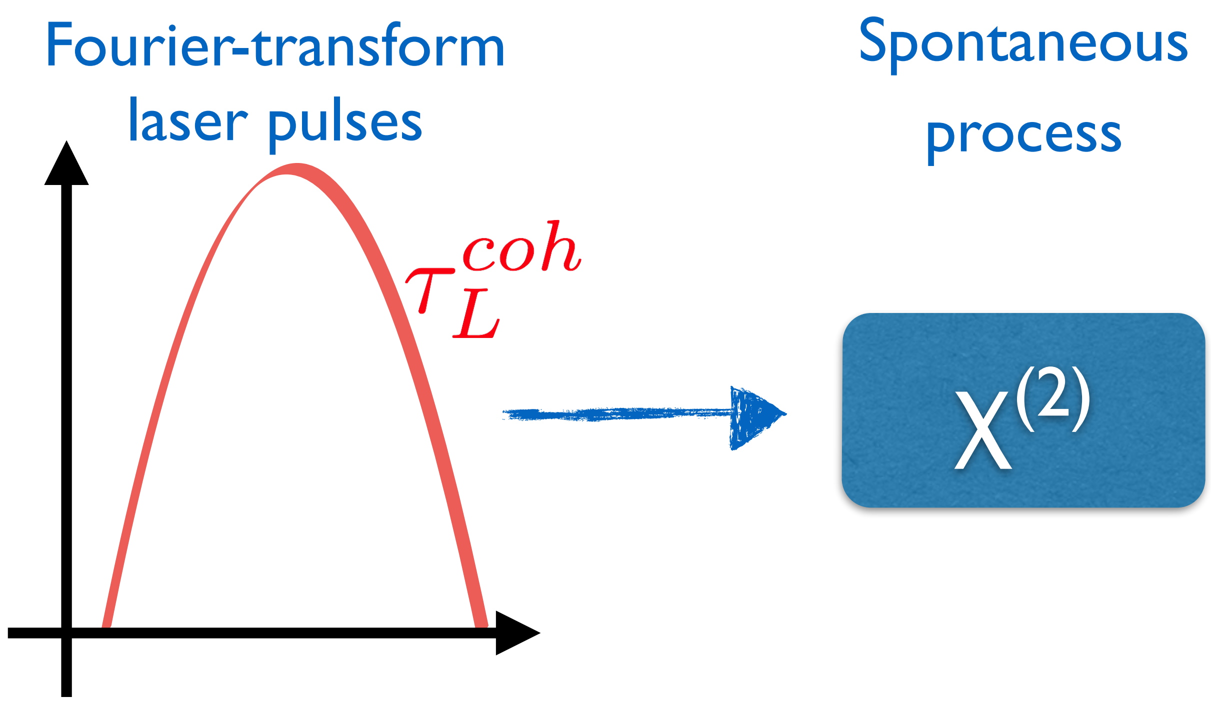

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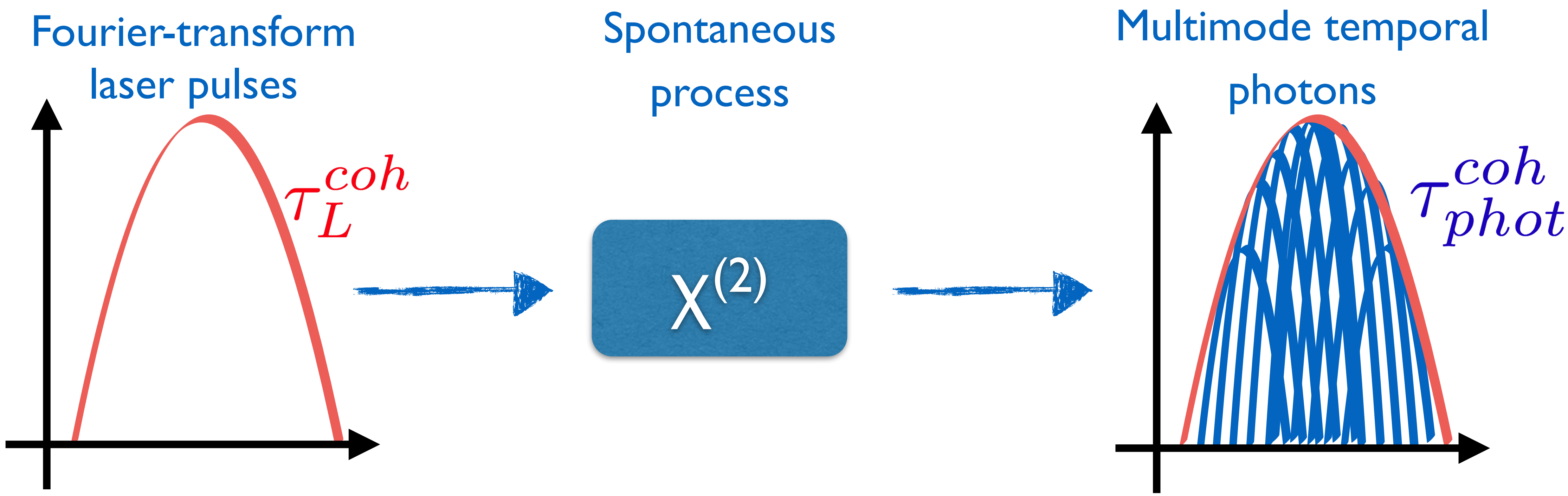

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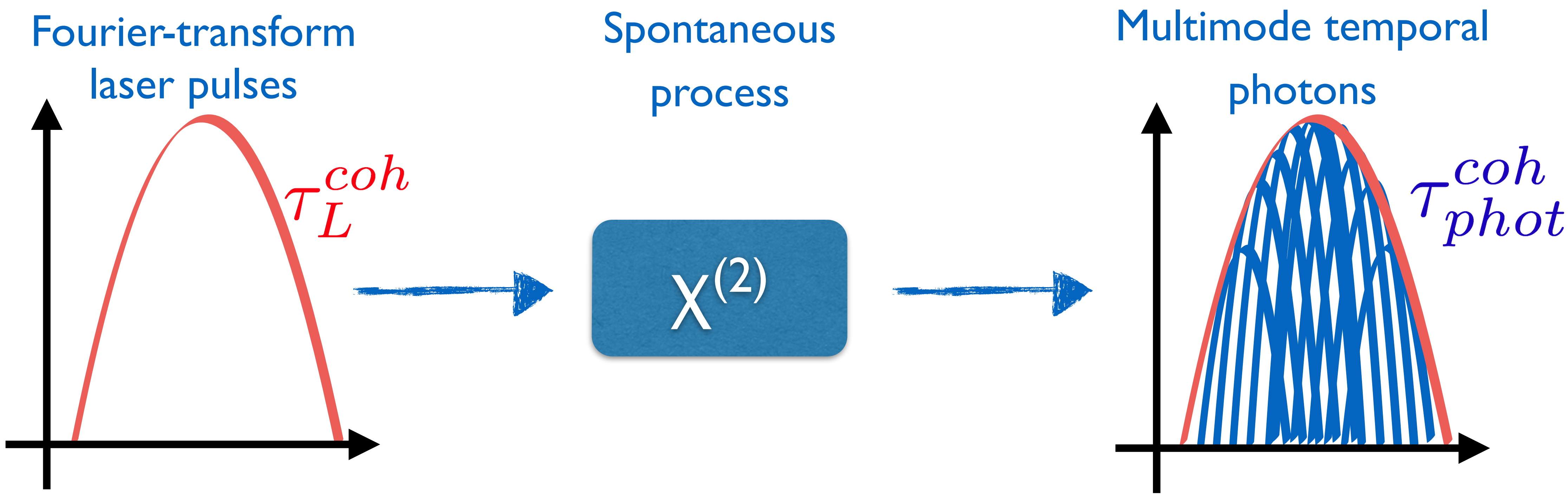

- **HBT setup without the heralding mode**

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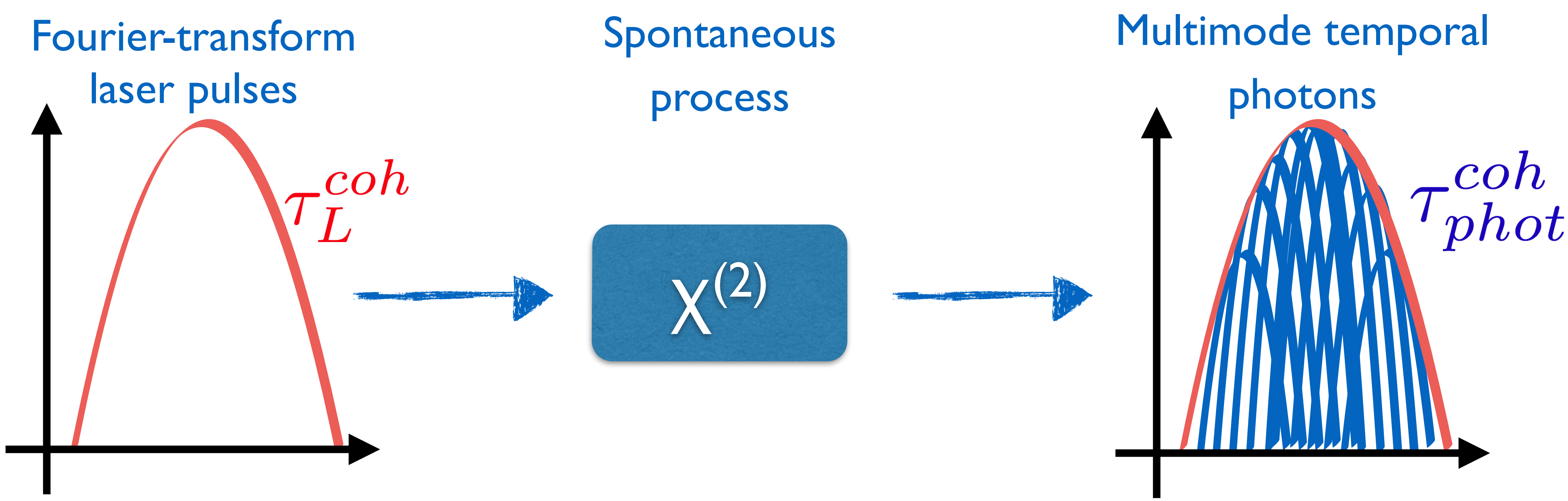

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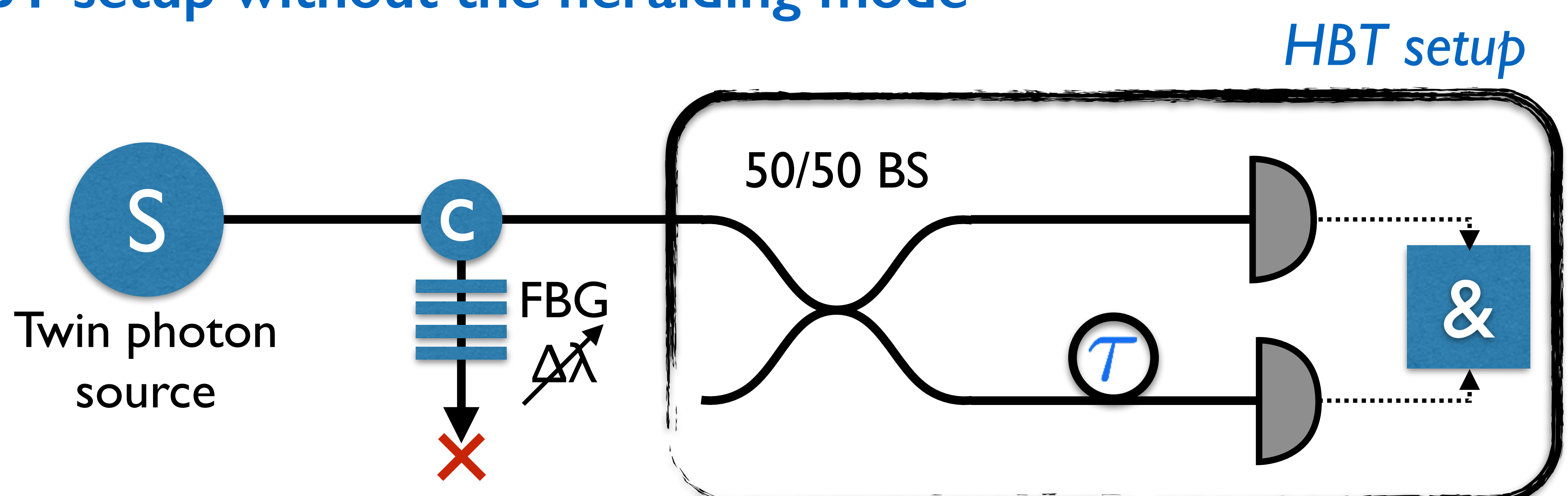

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P. Aboussouan *et al.*, PRA **81**, 021801(R) (2010)

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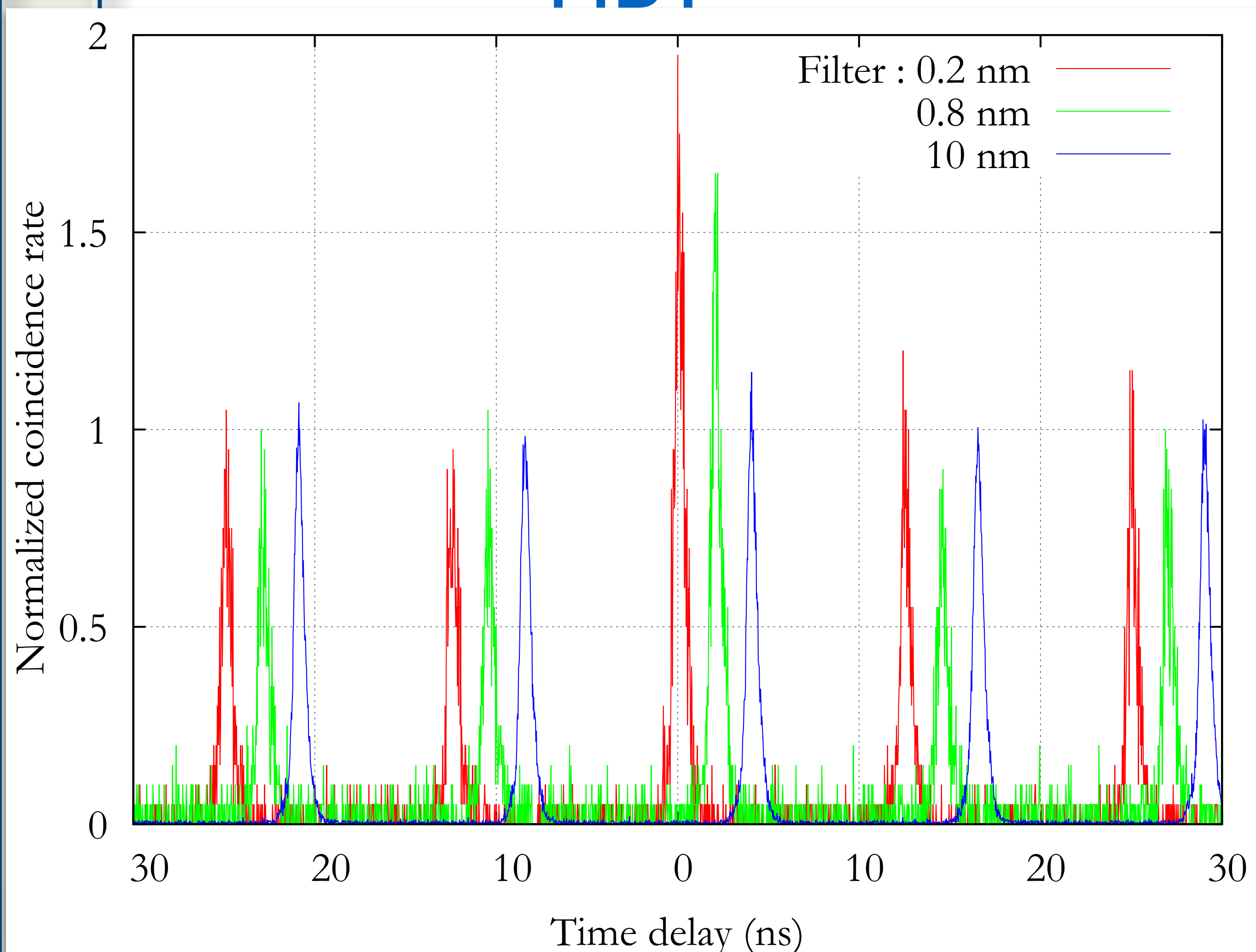

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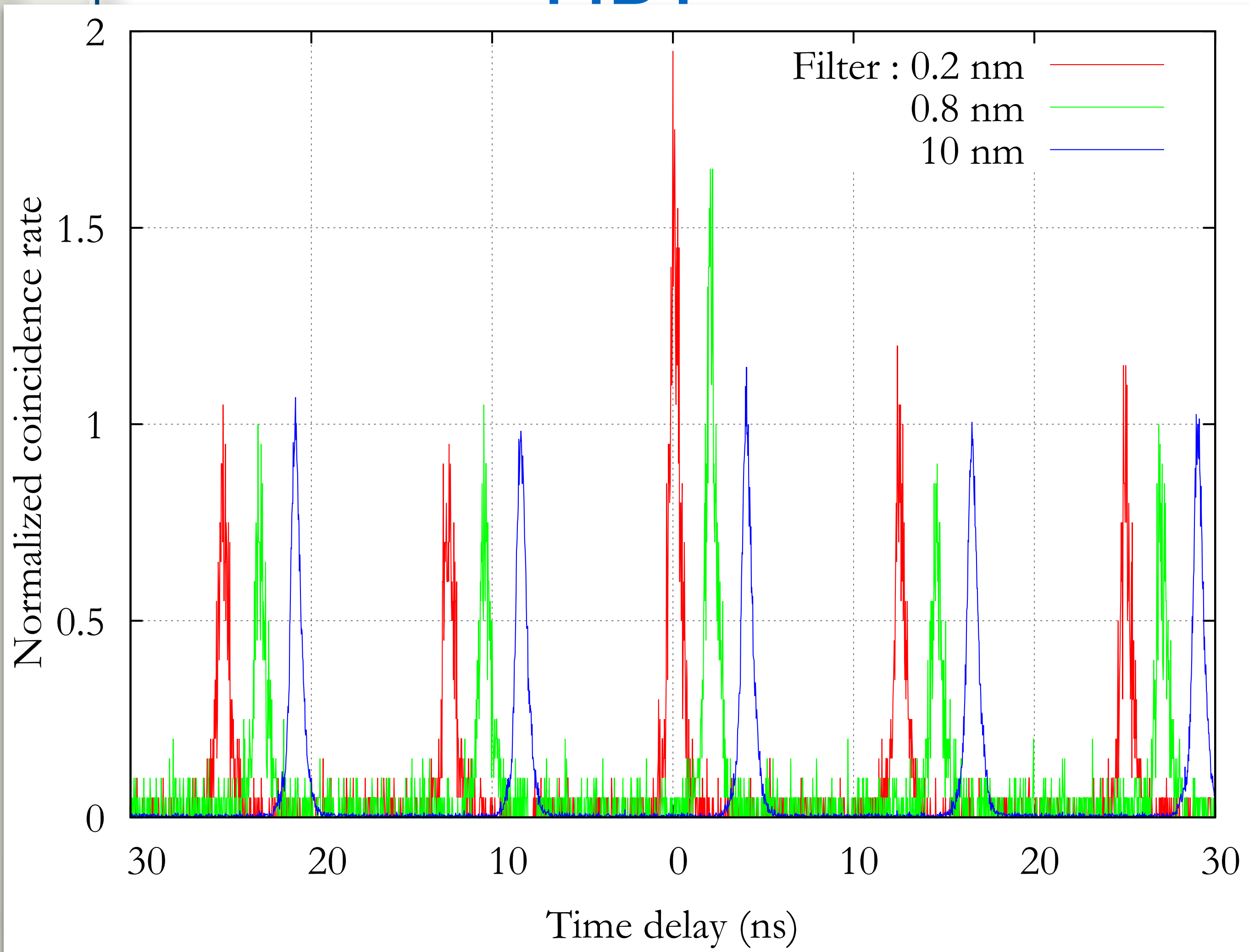

Thermal stat. ➜ bunching effect

Poissonnian stat. ➜ coherent state

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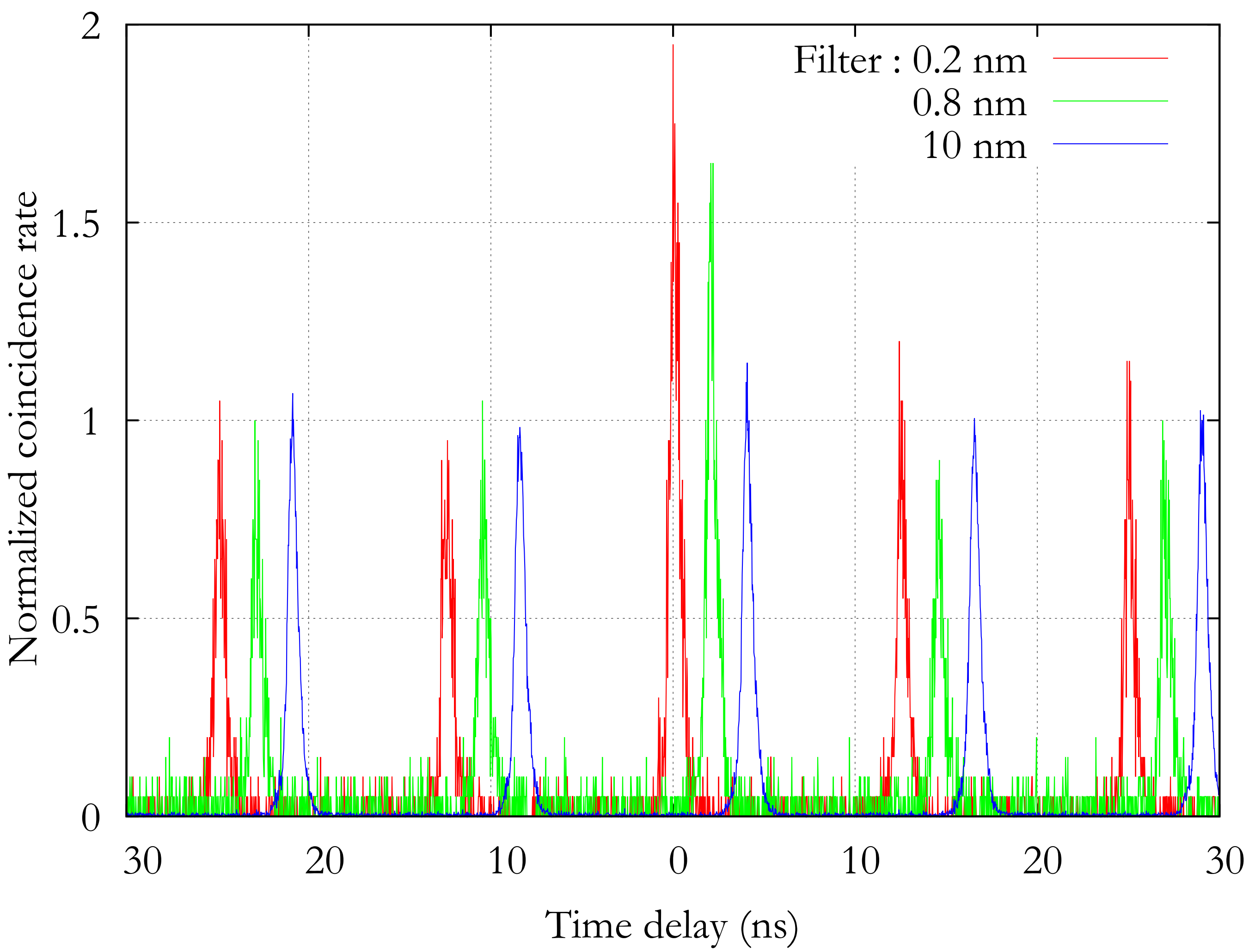

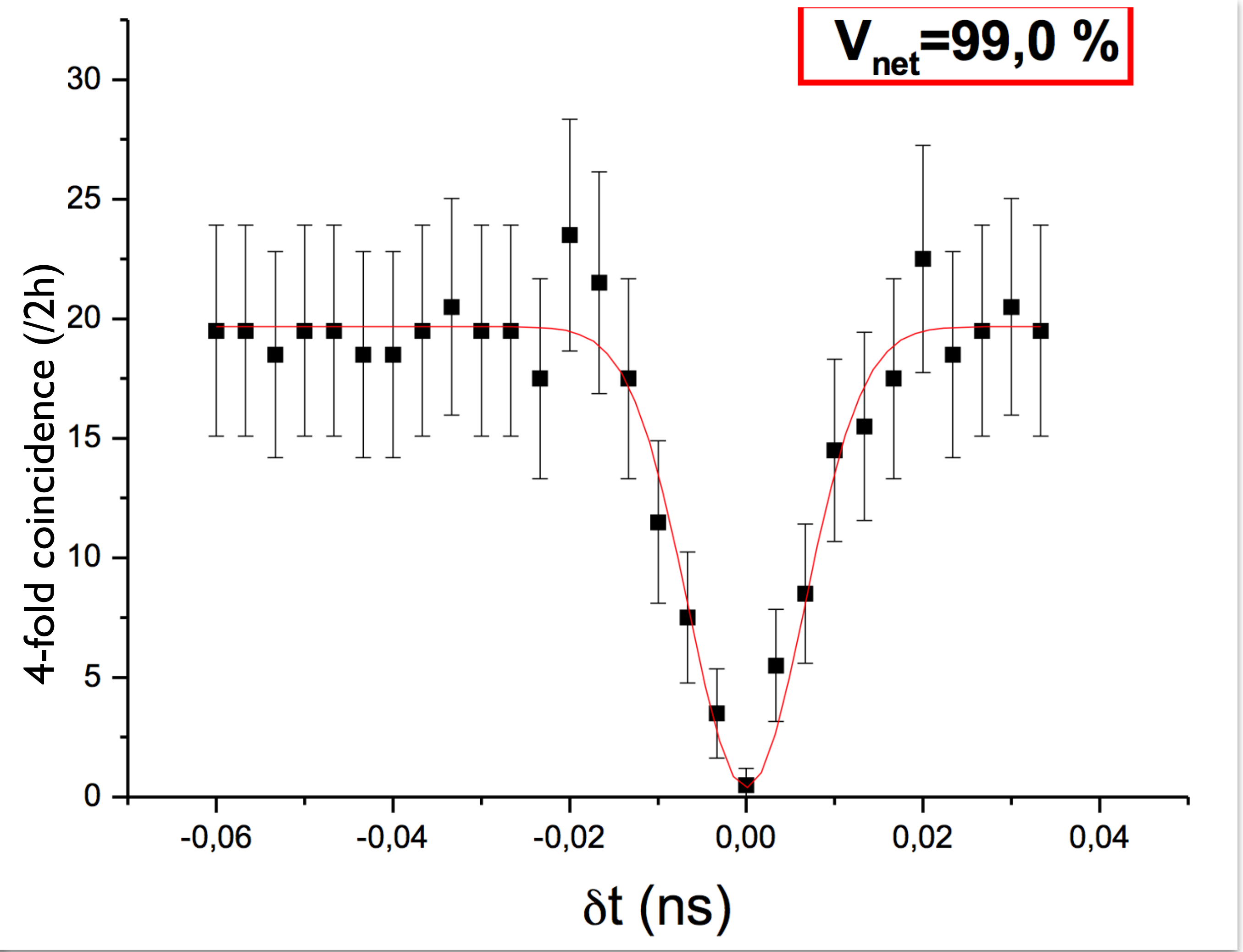

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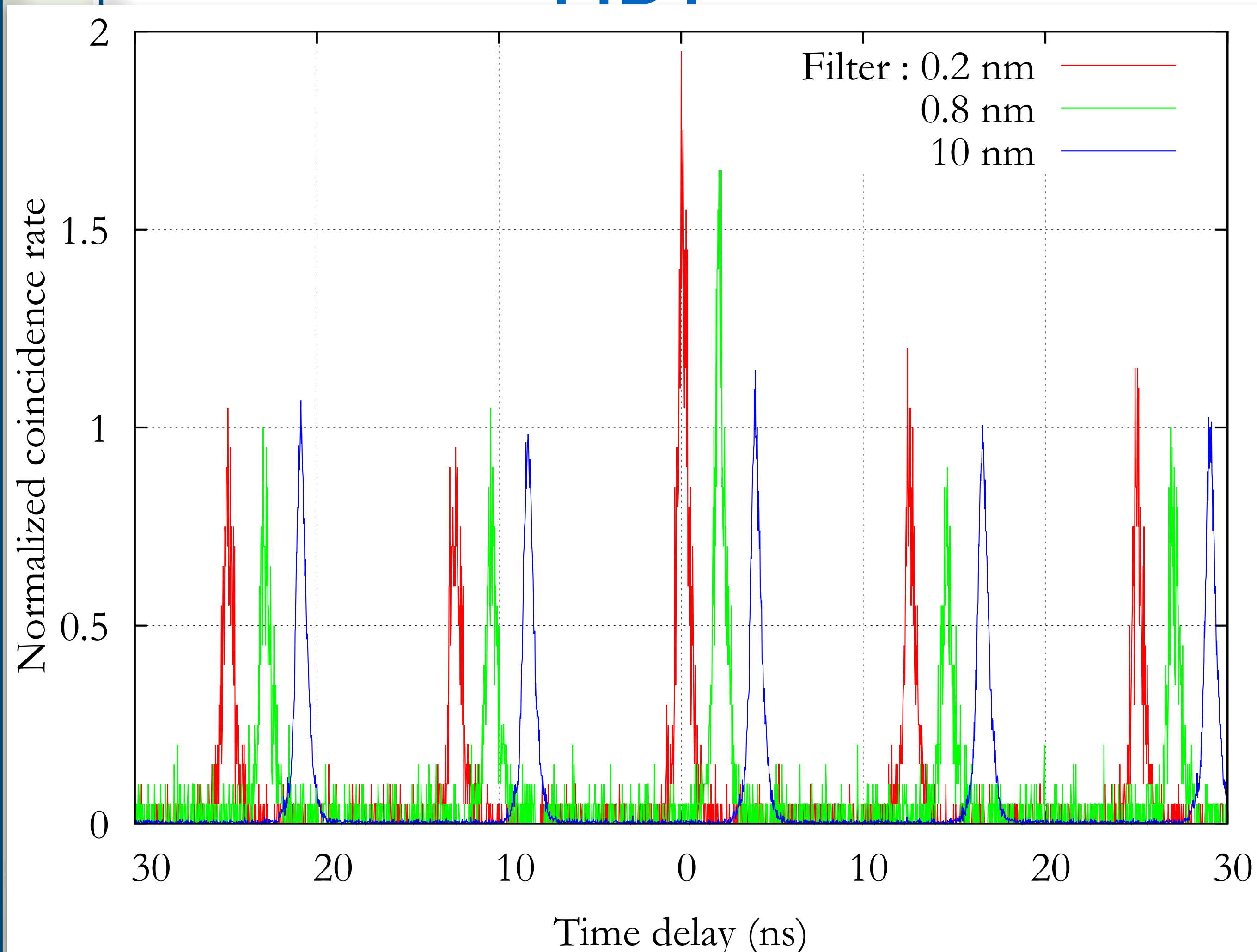

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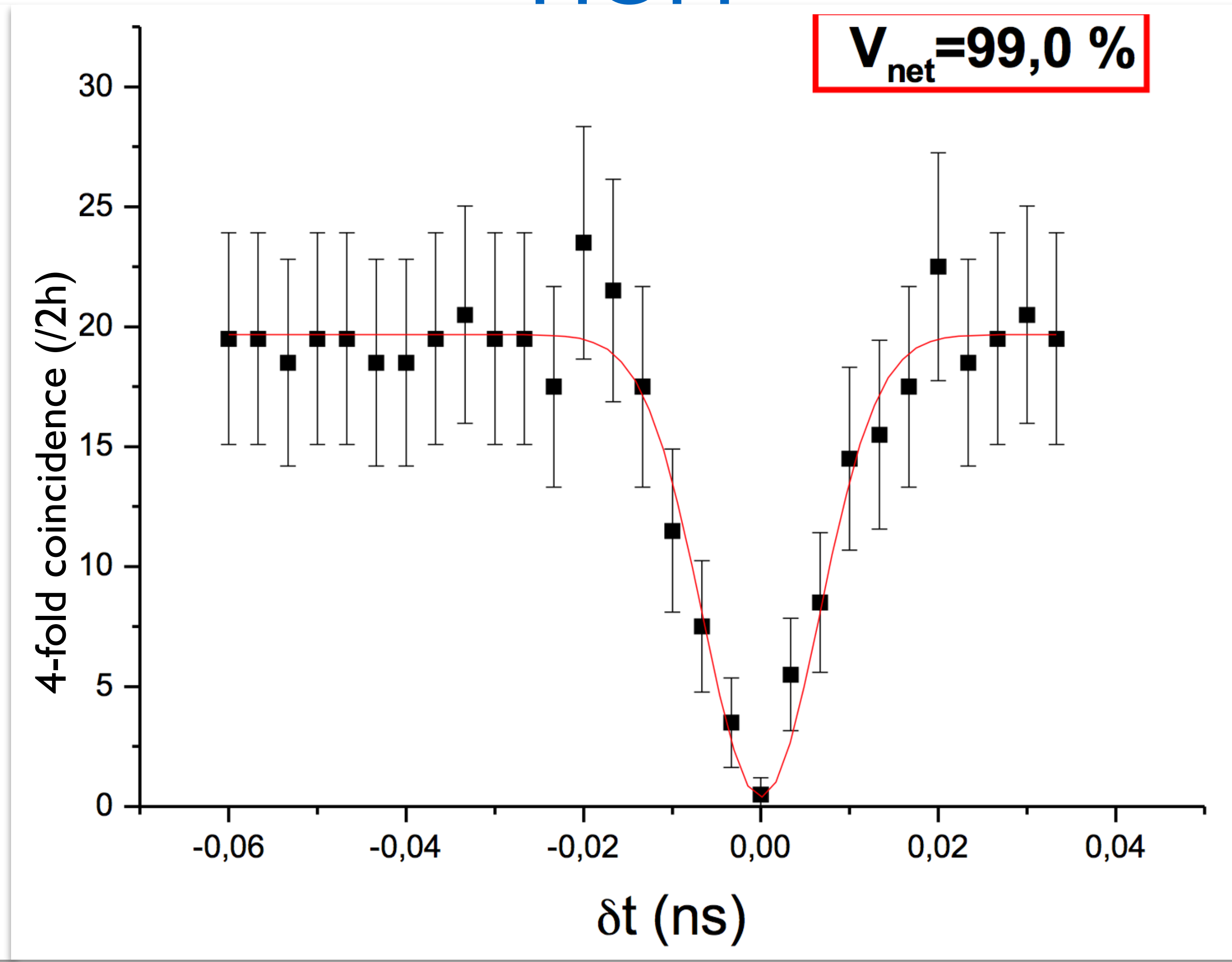

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Max HOM interf. VIS (pure photons)

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Visibility limited to 33%

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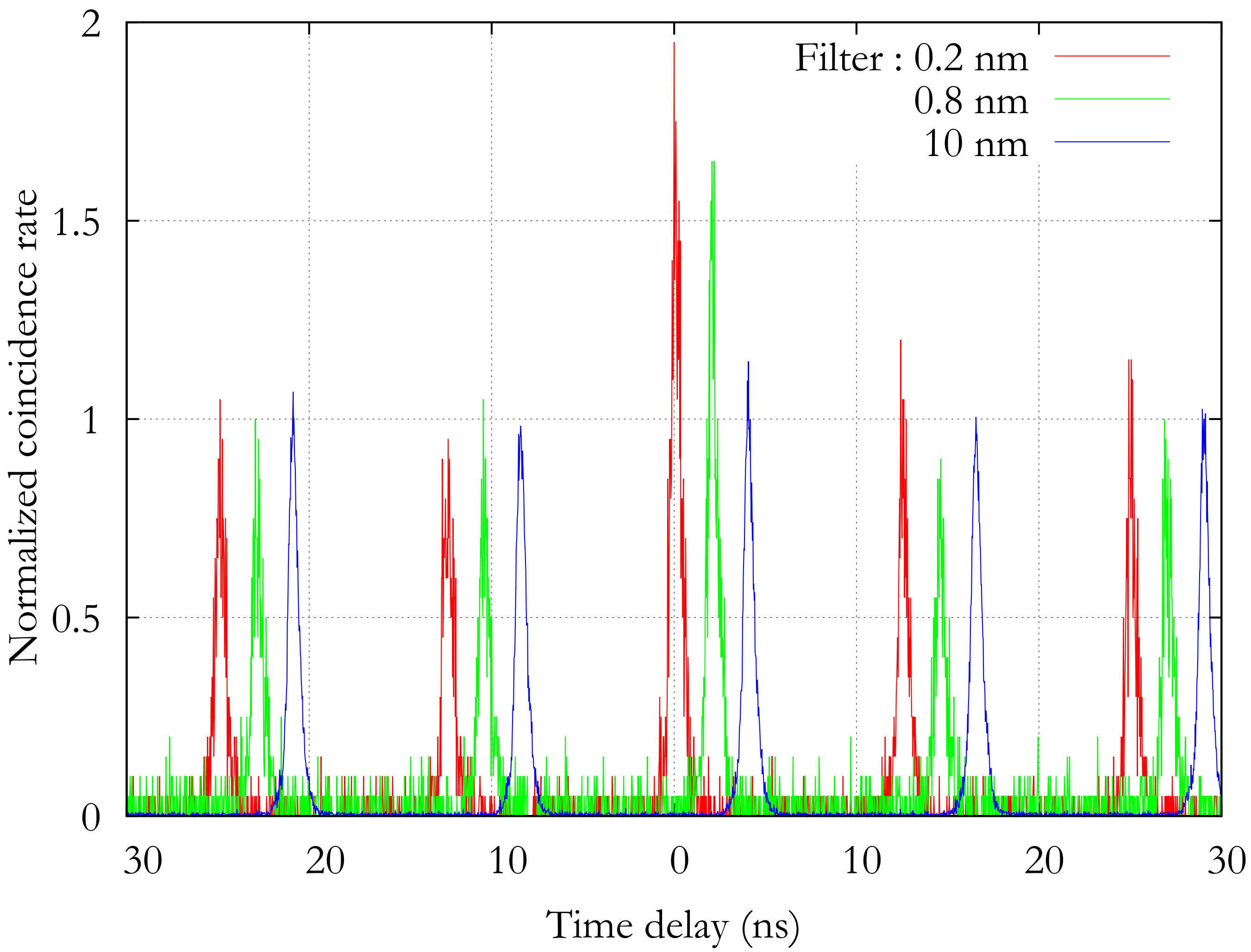

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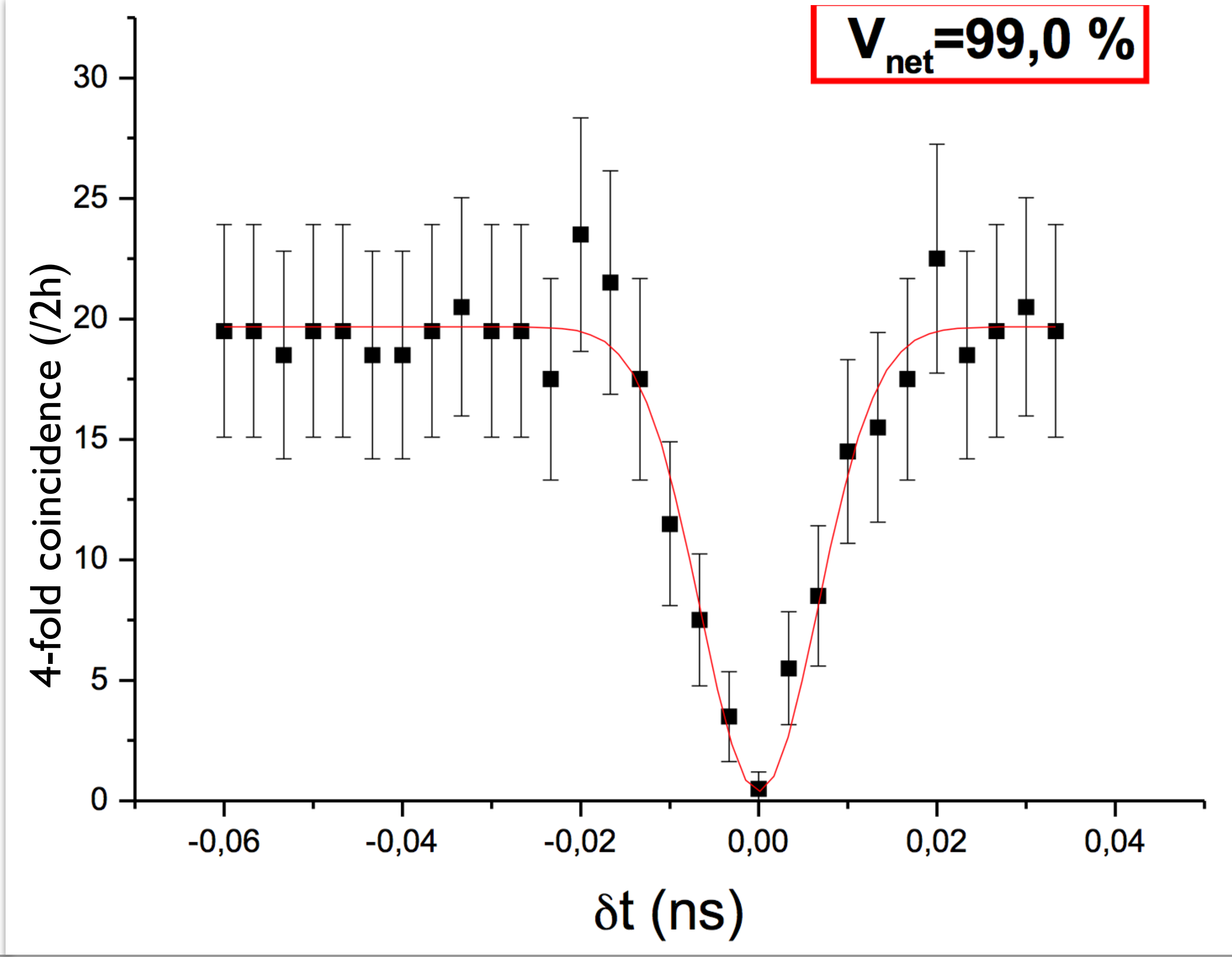

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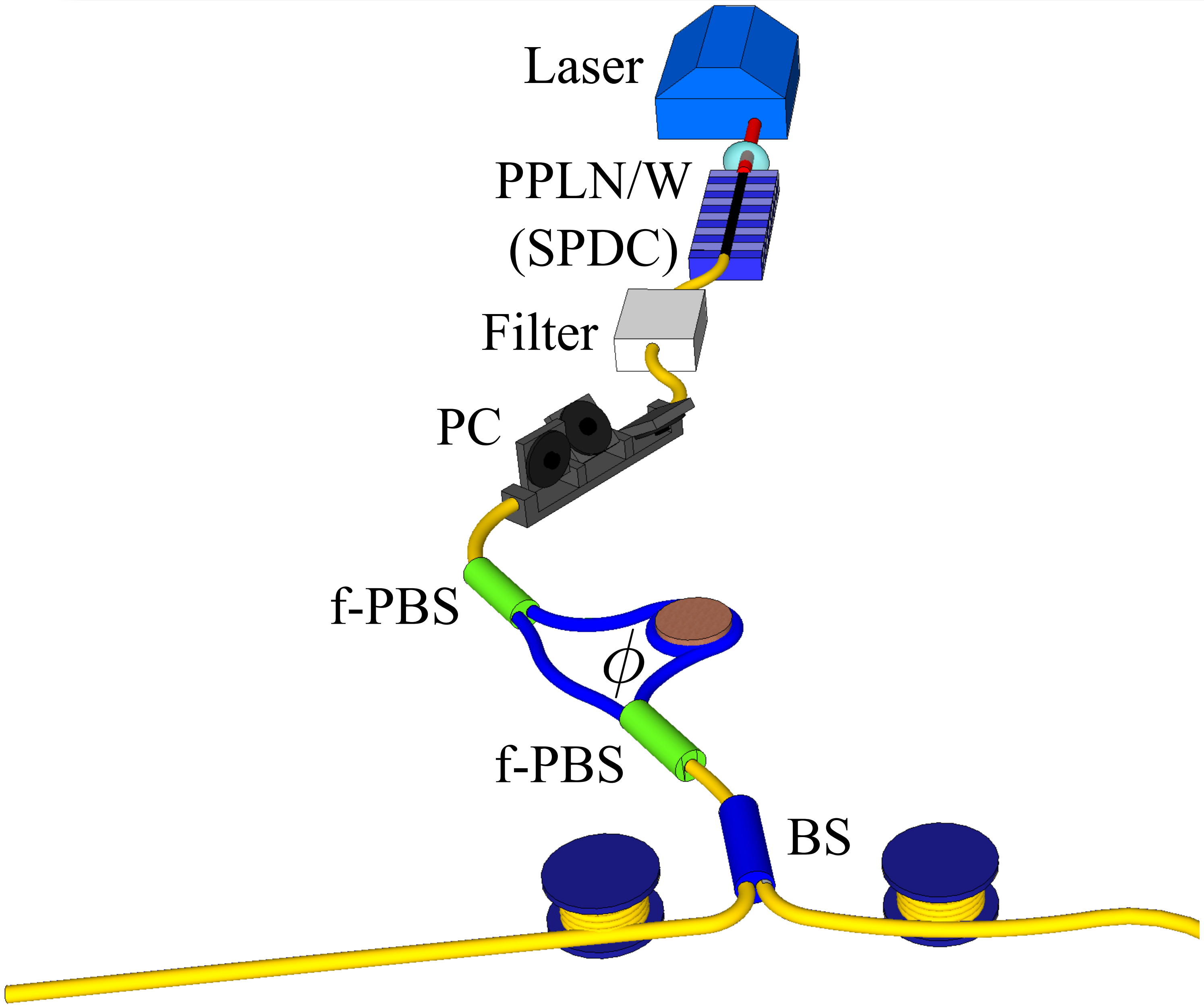
Outline

1. Introduction
2. HBT for characterizing single photon sources (SPS)
3. HBT for characterizing photon pair sources
    1. A versatile source of polarization entangled photons
    2. Cross-correlation function & coherence time of the emitted photons
    3. Bell inequality type measurements

3.1 A versatile polarization entangled photon pair source



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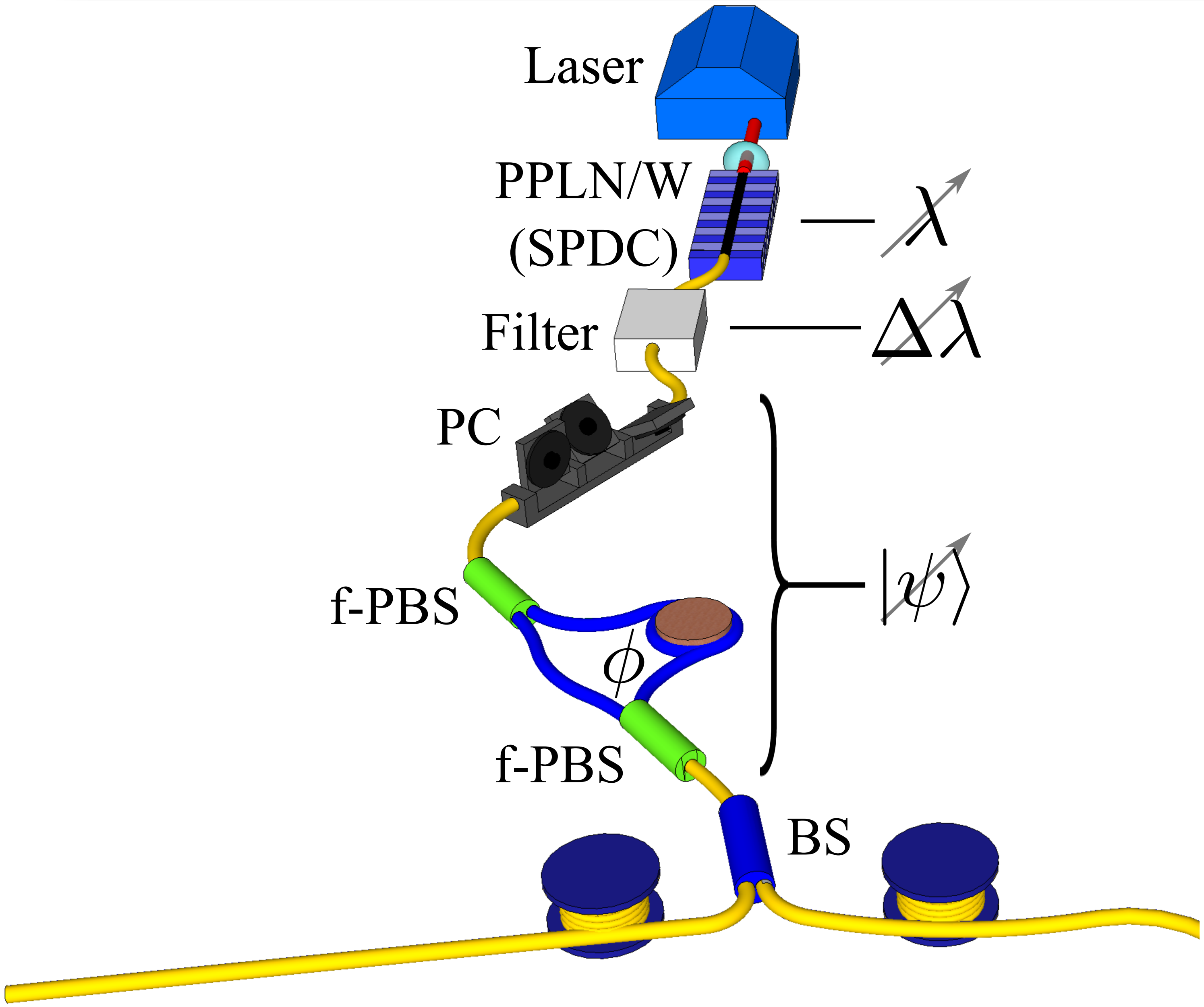

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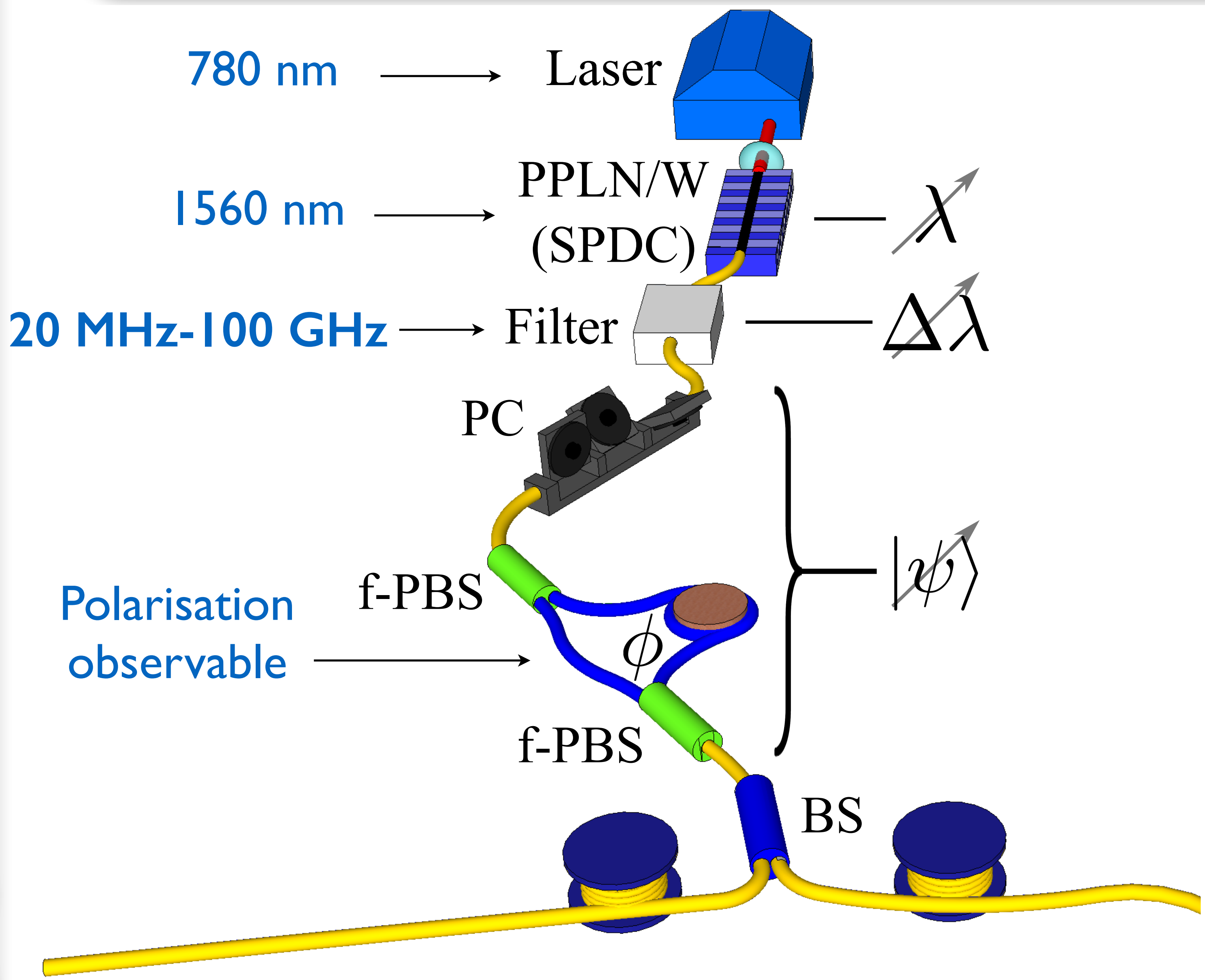

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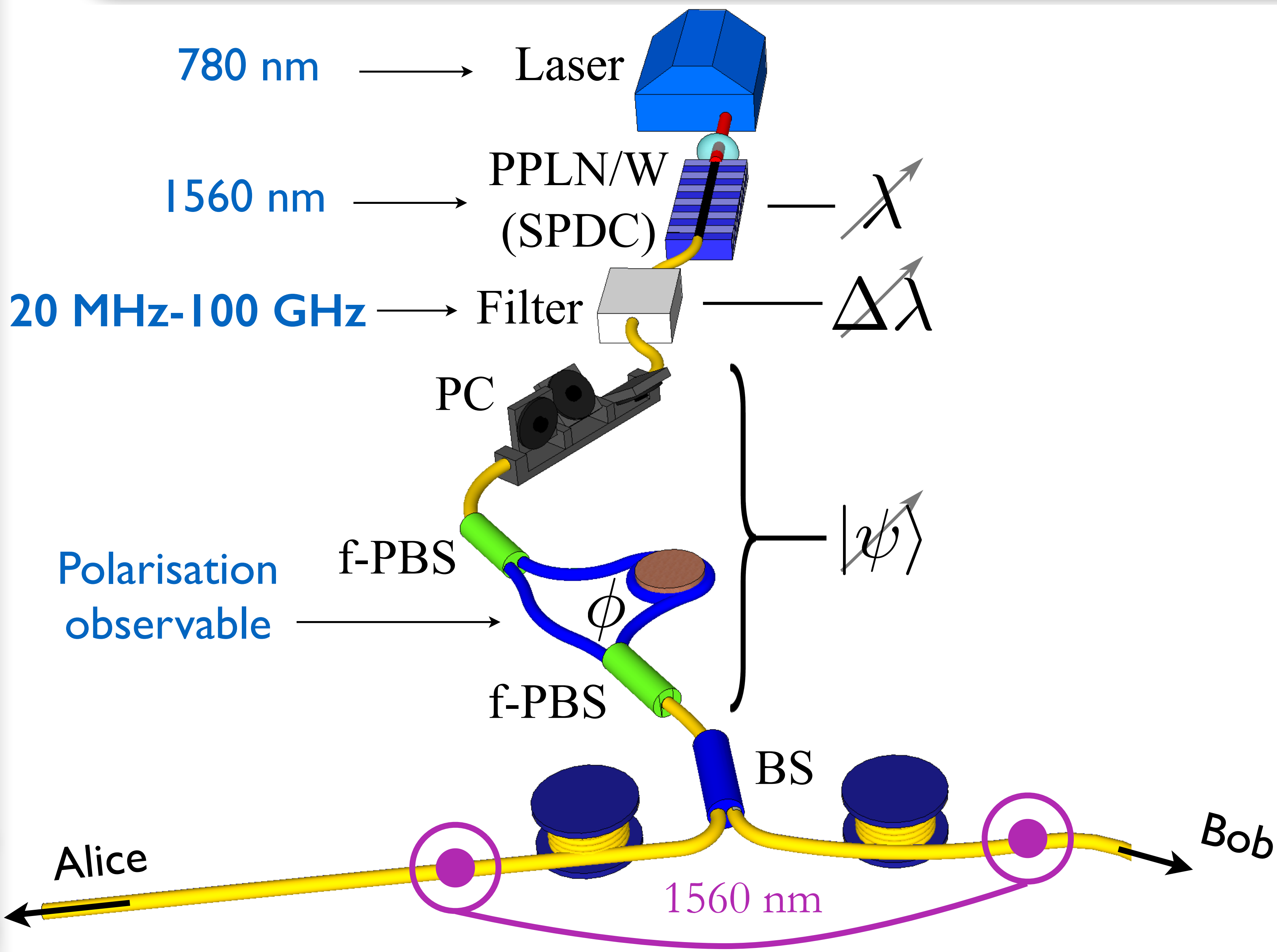

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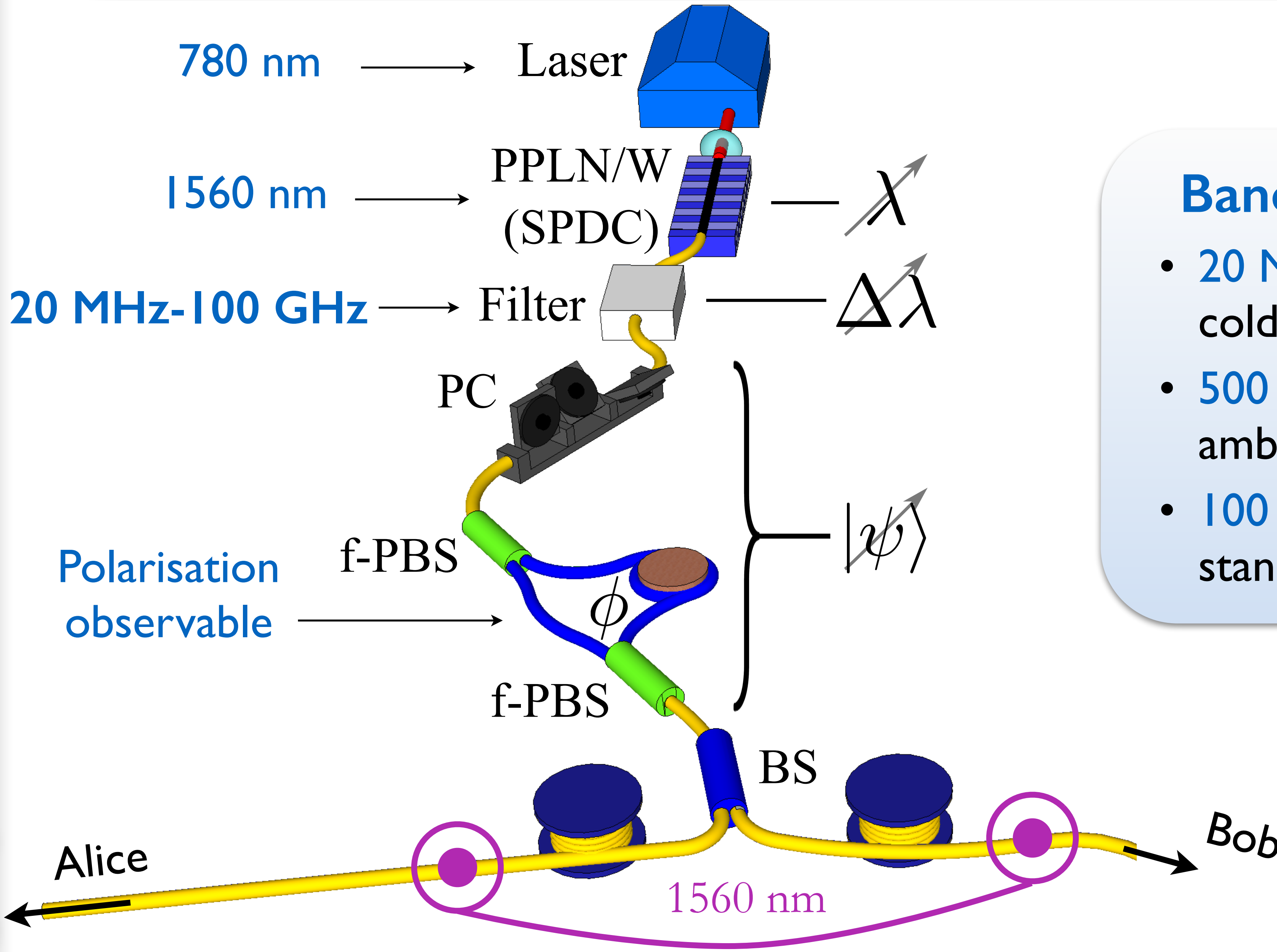


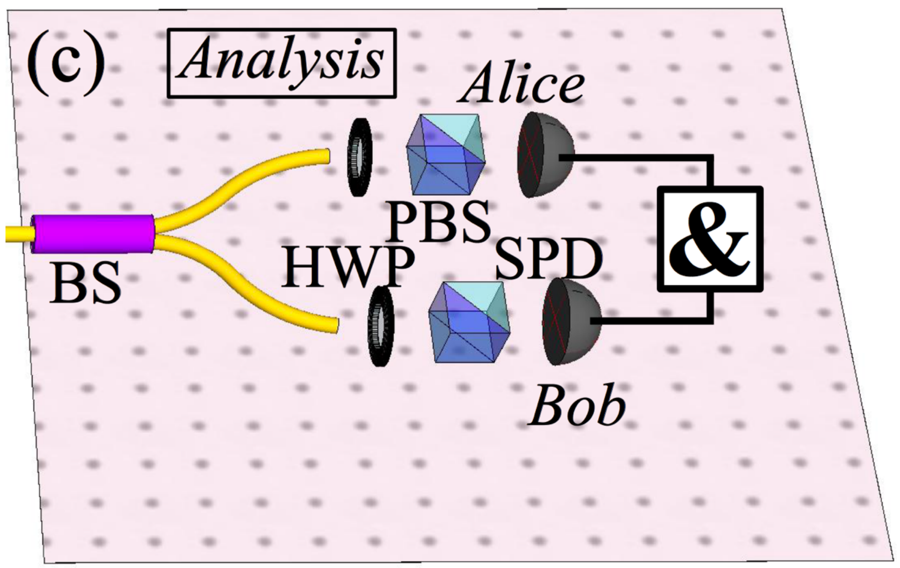
Bandwidth versatility

- 20 MHz ➜ Interface with cold atoms Q-memory
- 500 MHz ➜ Interface with ambiant T atomic vapors
- 100 GHz ➜ Q-crypto in standard telecom channels

F. Kaiser *et al.*, Science [2012]
F. Kaiser *et al.*, Laser Phys. Lett. [2013]
F. Kaiser *et al.*, Optics Comm. [2014]

3.2 Cross-correlation function via coincidence mst

- **Tests with 3 FBG filters : 80 GHz, 540 MHz, 25 MHz**



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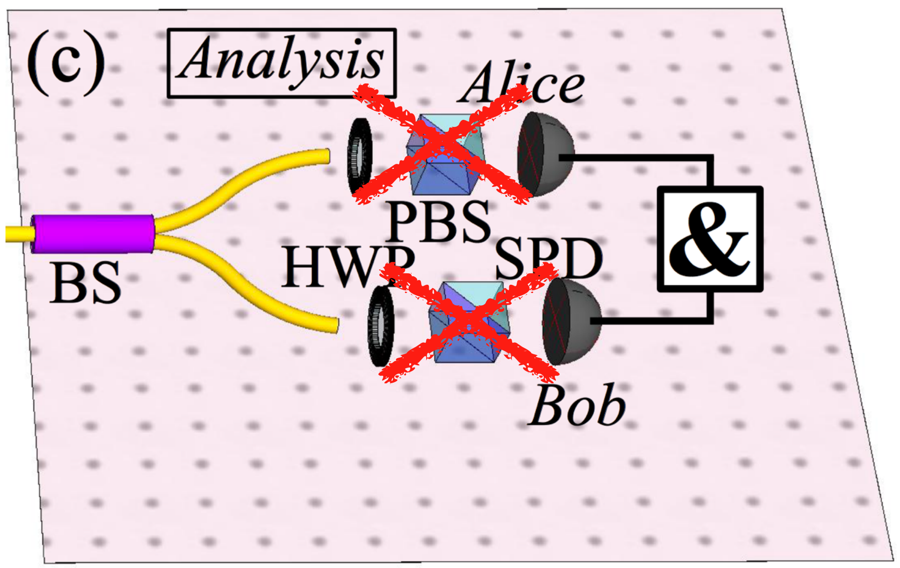

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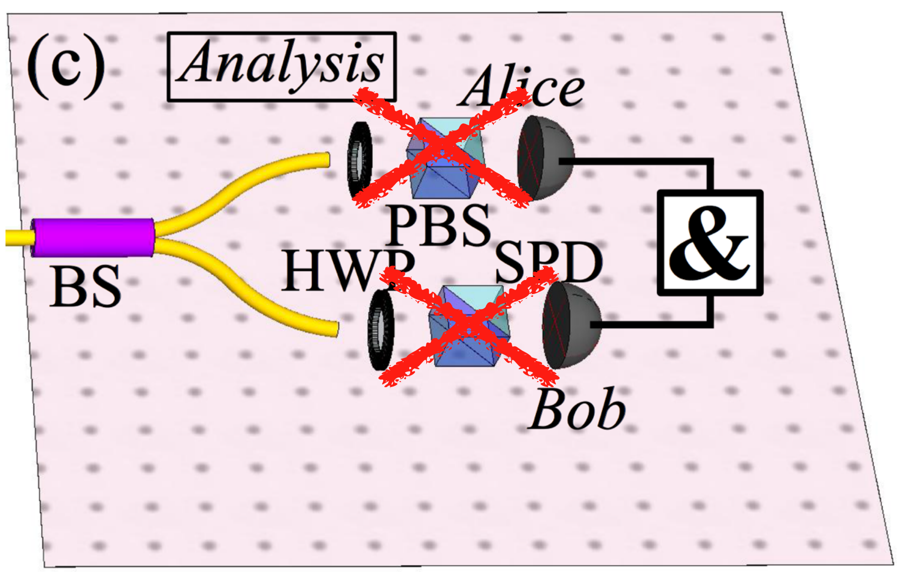

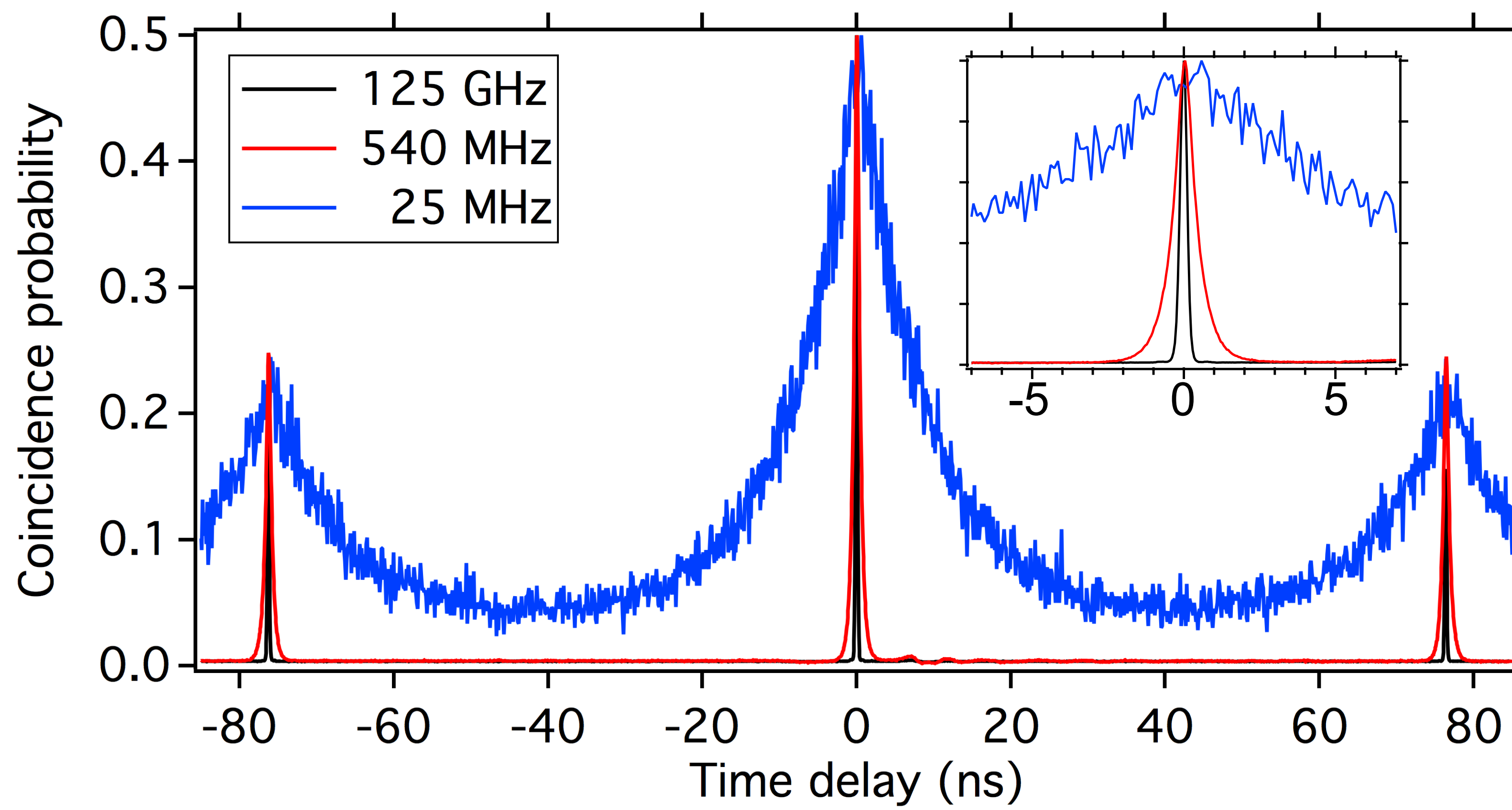

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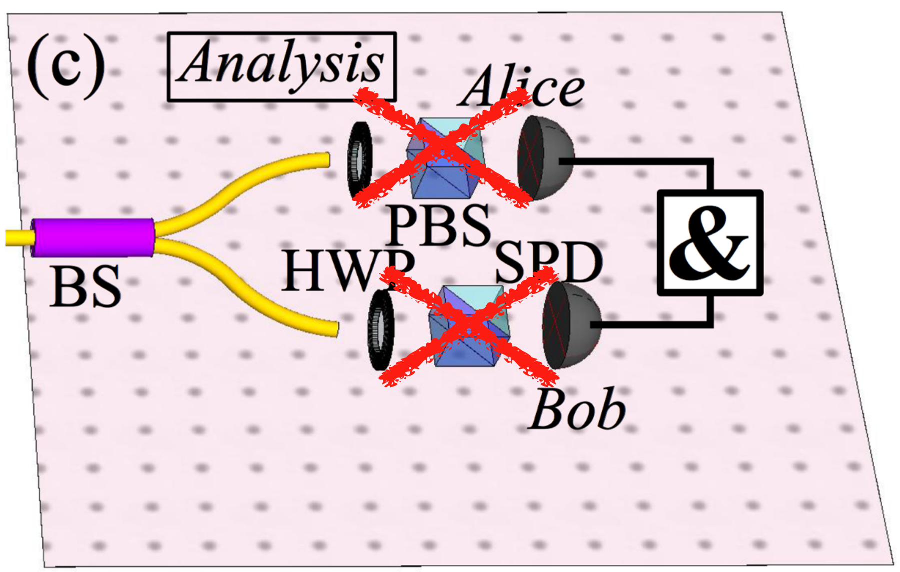

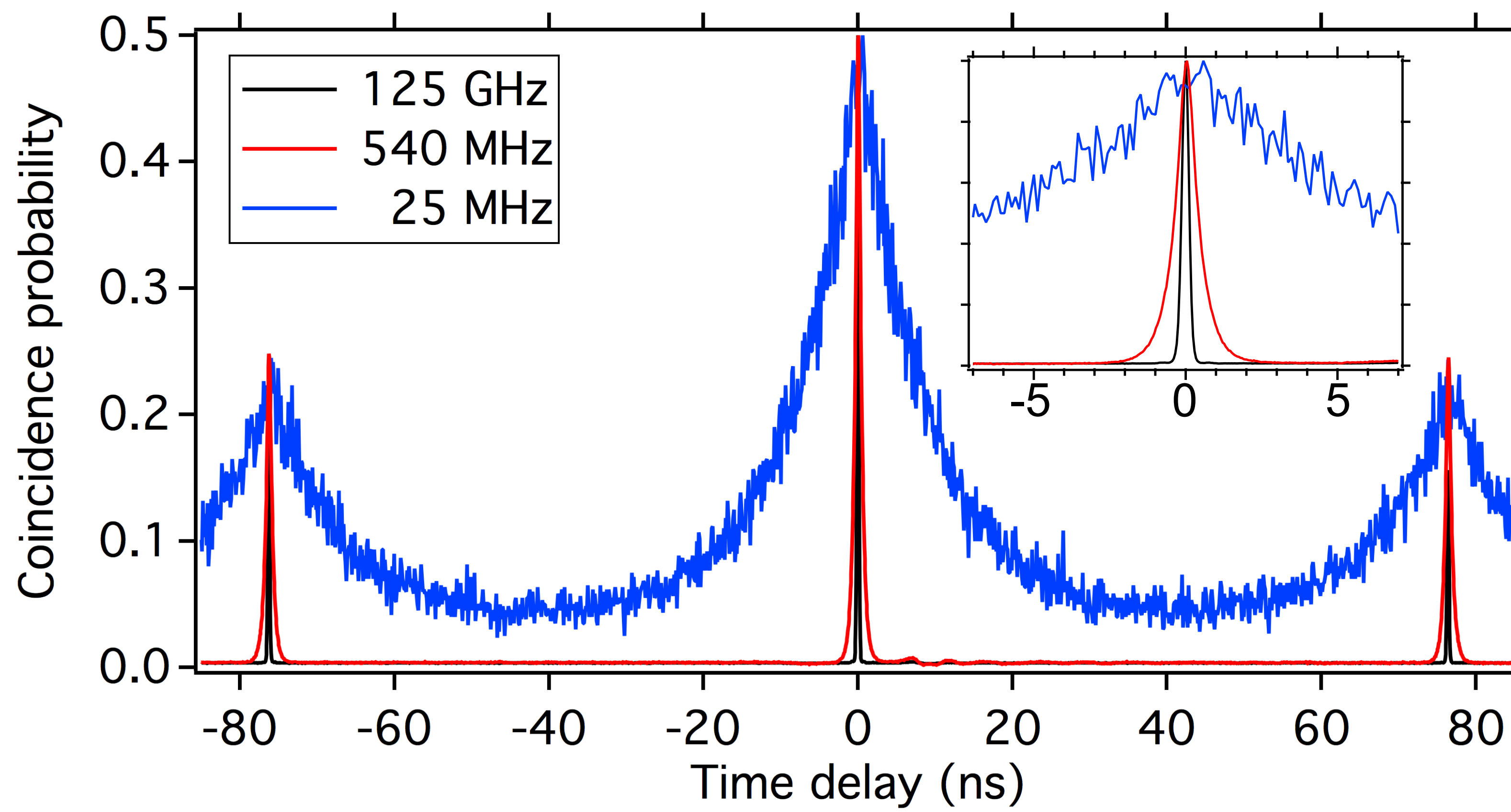

	τ_{phot}		$\Delta\nu$
black line	440 ps		125 GHz
red line	0.8 ns	⇔	540 MHz
blue line	15.6 ns		25 MHz

3.2 Cross-correlation function via coincidence mst

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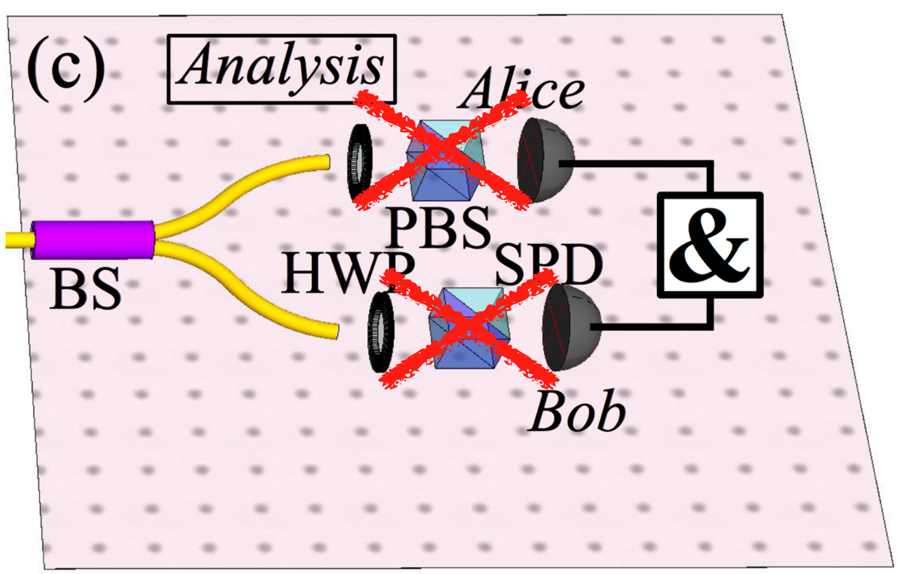
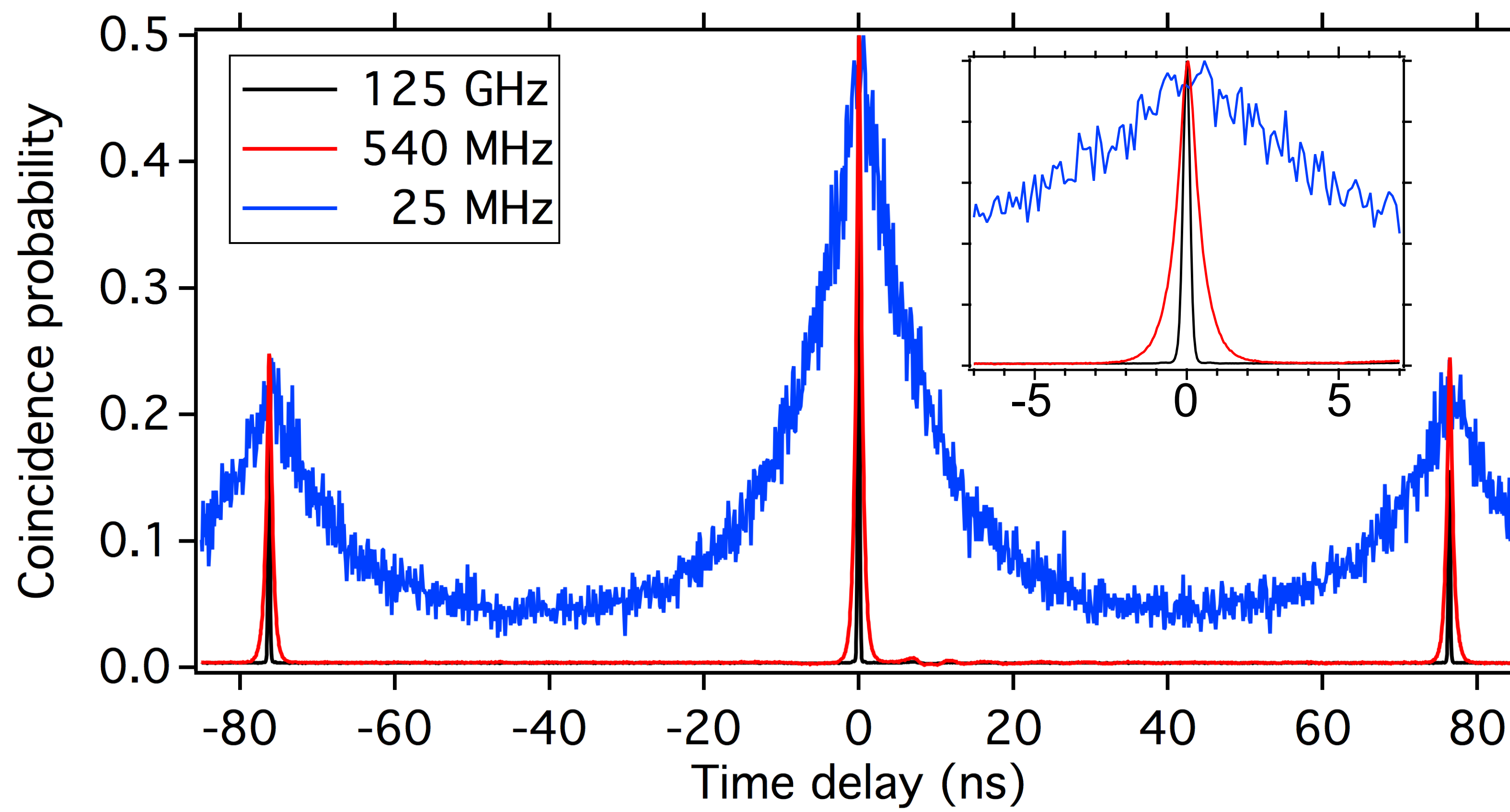




	τ_{phot}		$\Delta\nu$
(black line)	440 ps		125 GHz
(red line)	0.8 ns	$\Leftrightarrow$	540 MHz
(blue line)	15.6 ns		25 MHz

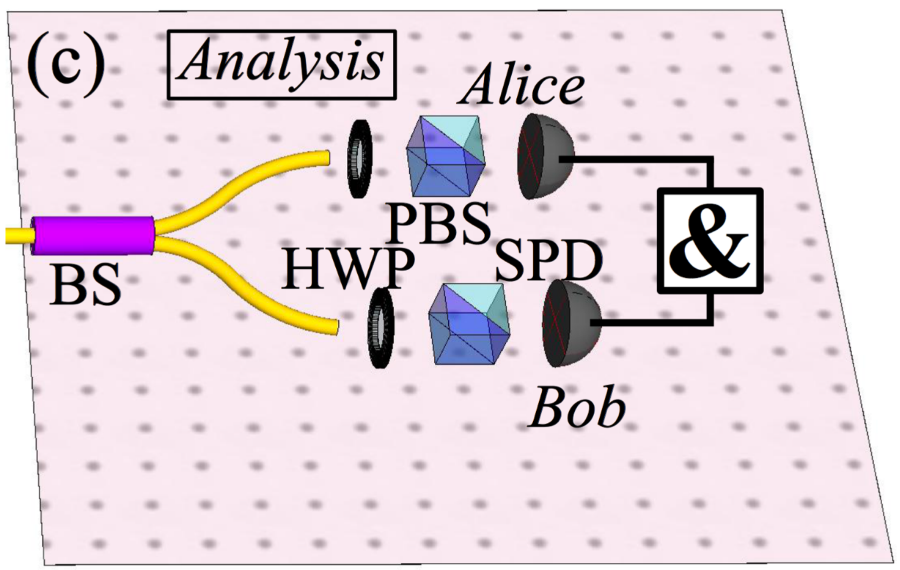
From the CAR

➜ Clear violation of the Cauchy-Schwartz inequality

➜ Twin photons are emitted simultaneously, at the quantum level

3.3 Bell inequality type mst

- **Tests with 3 FBG filters**



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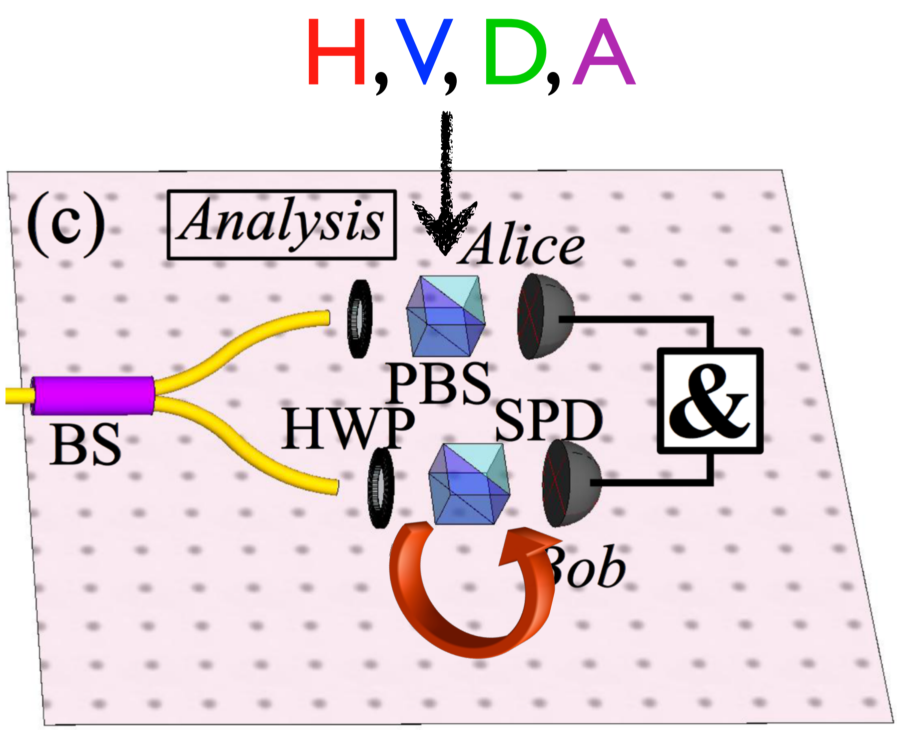
3.3 Bell inequality type mst

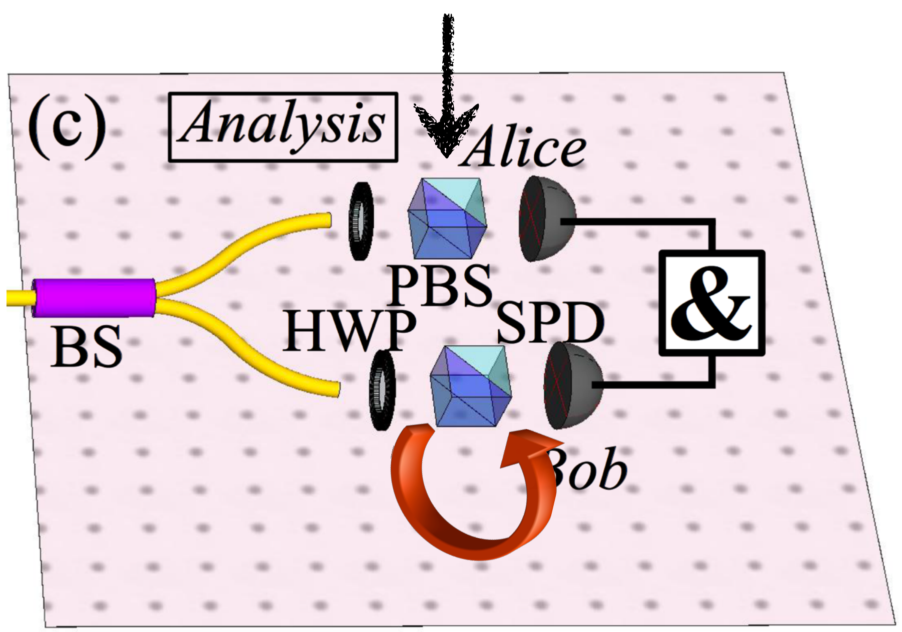
- **Tests with 3 FBG filters**



3.3 Bell inequality type mst

- Tests with 3 FBG filters

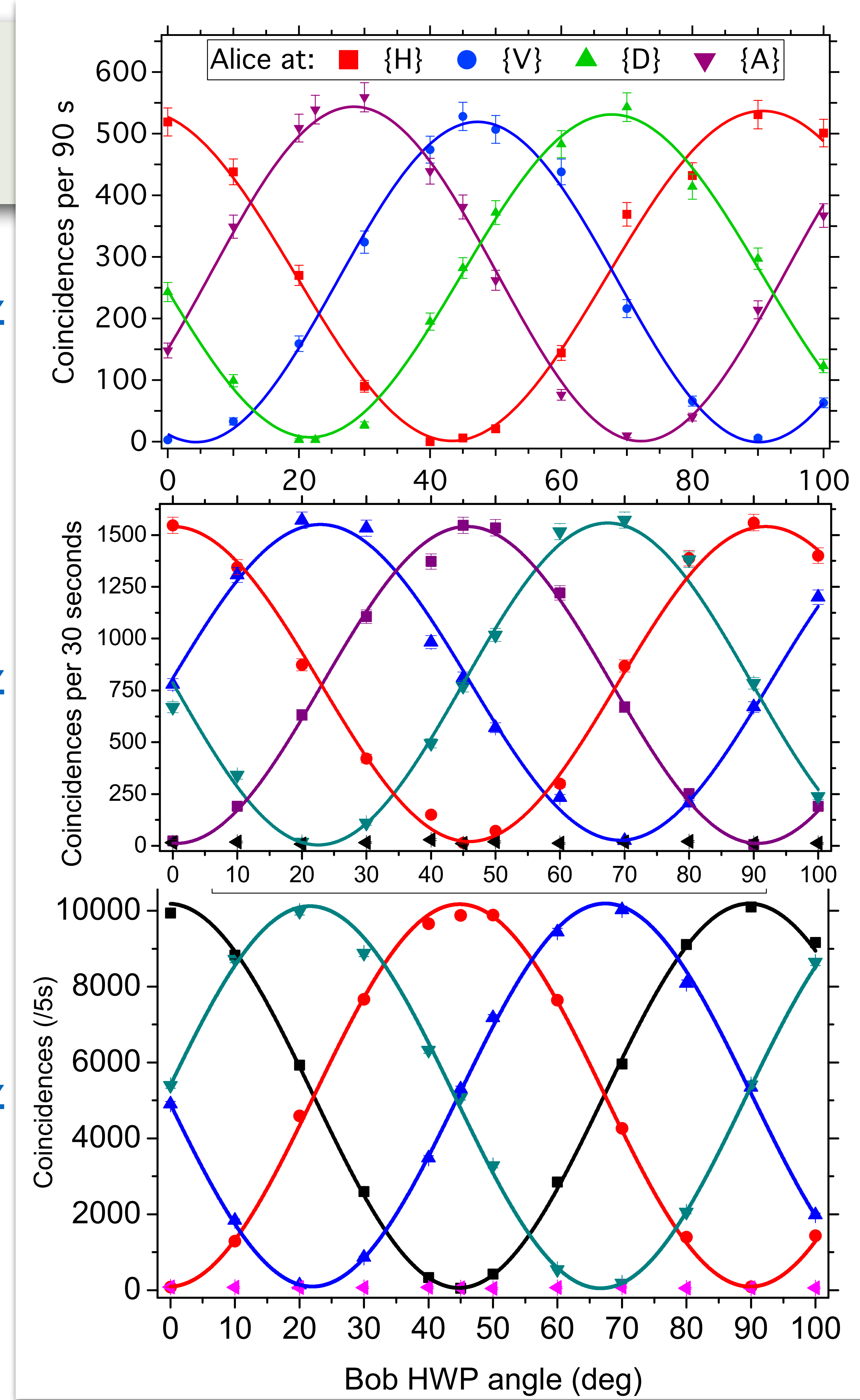
H, V, D, A



80 GHz

540 MHz

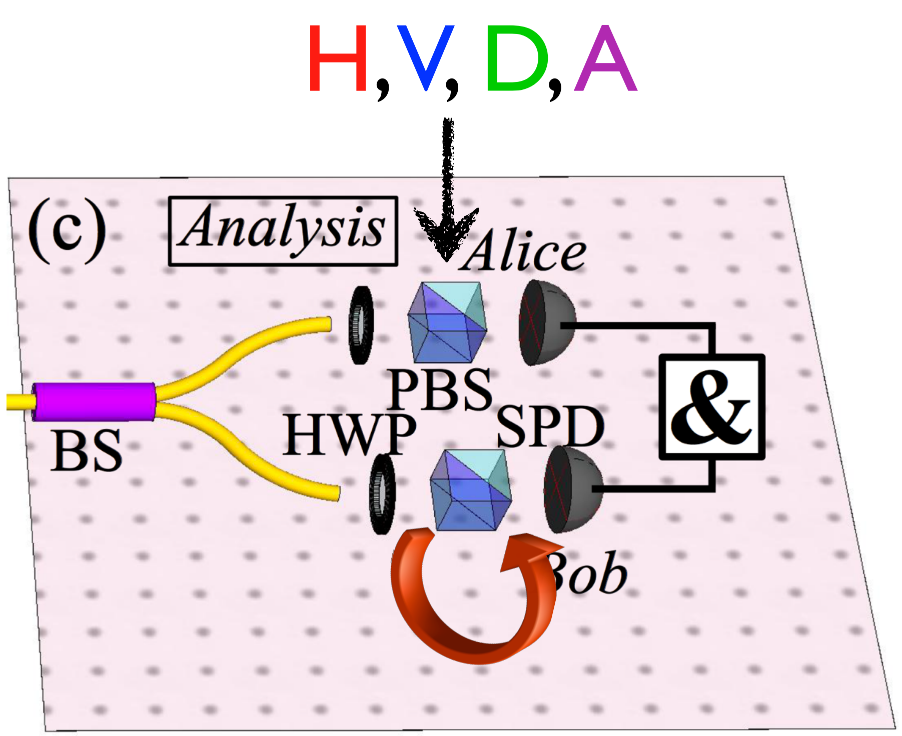
25 MHz



3.3 Bell inequality type mst

- Tests with 3 FBG filters

80 GHz

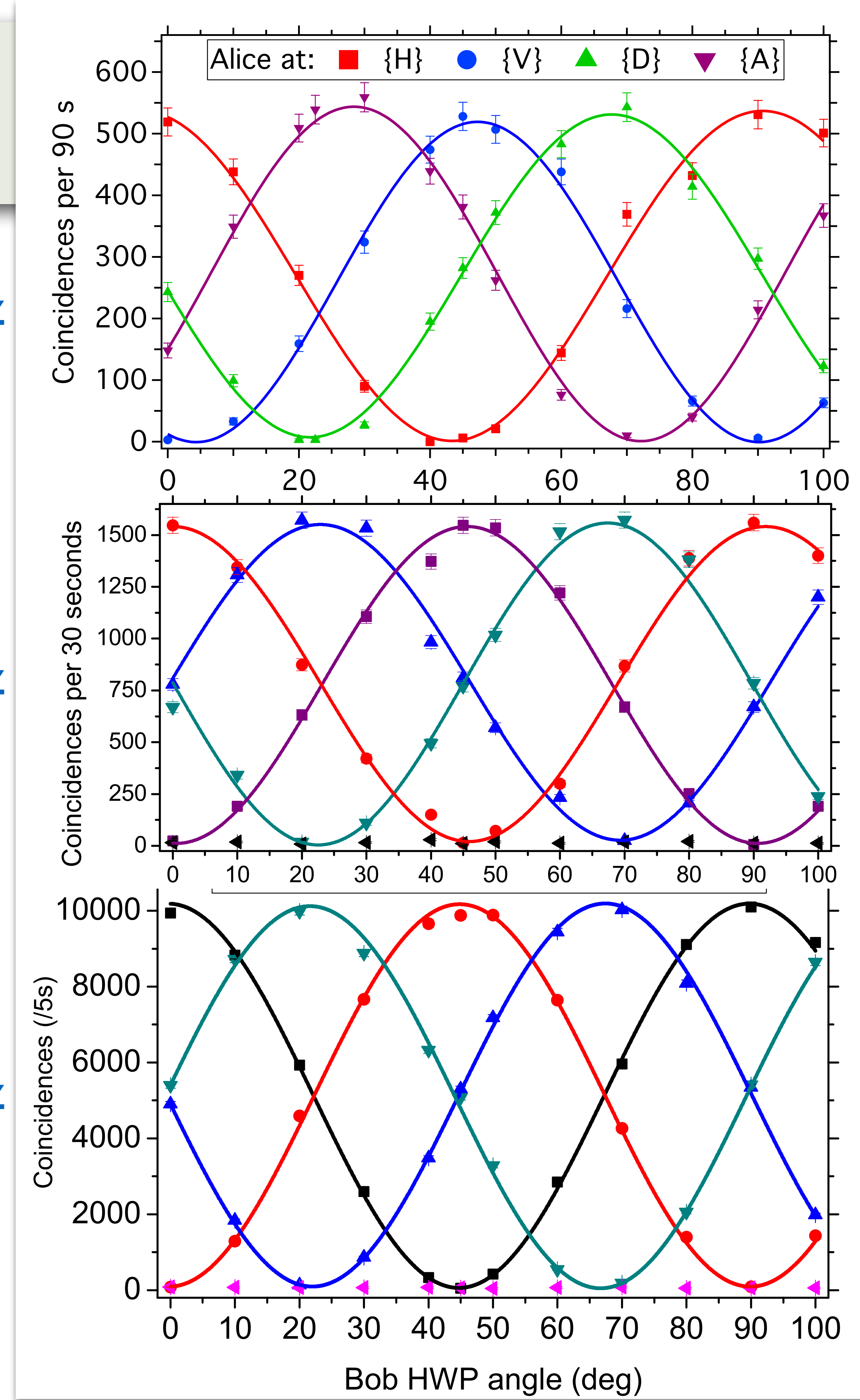


540 MHz

25 MHz

	Standard H,V,D,A
Vraw	> 99% all

Excellent quality entanglement



Conclusion

1. **HBT-type setups play an important role in Q optics & com.**
    1. Help characterizing single photon and paired photon sources
    2. Permit connecting heralded SPSs in a quantum network
    3. Offer direct measurement of the photons' coherence time
2. **Particular attention has to paid to**
    1. Single photon detectors (noise, timing jitter)
    2. HOM effect requires photons in a pure temporal mode
    3. Losses over the quantum channels

L'équipe QILM + OptiNiL

UMR 7336

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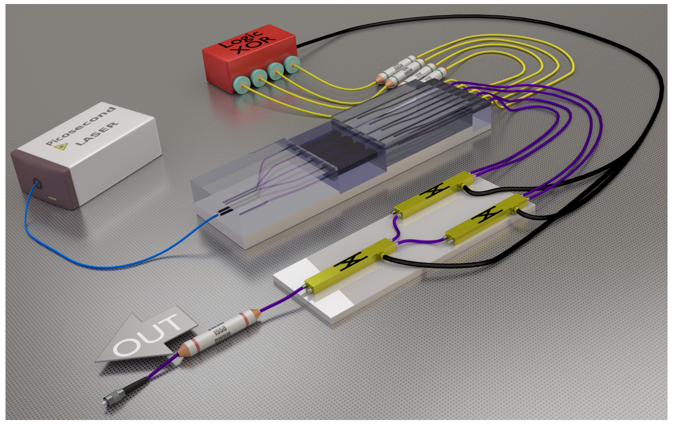

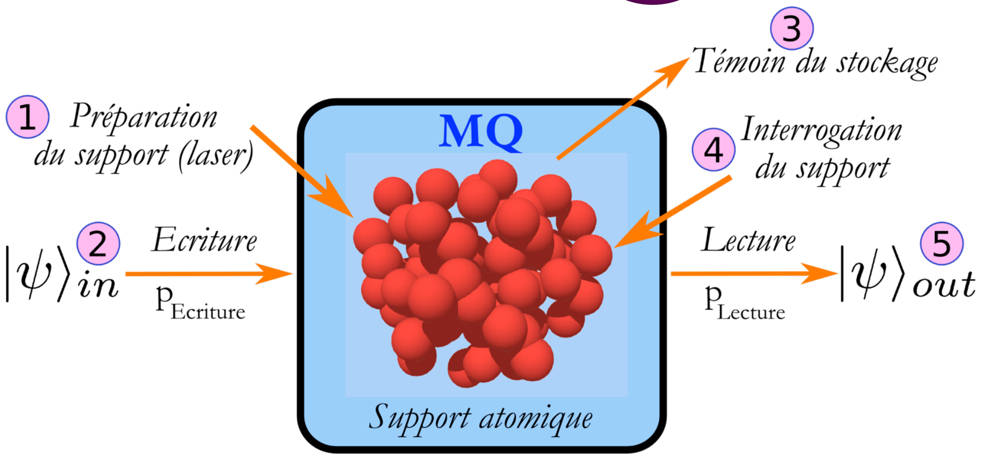

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